Universität für Bodenkultur Wien
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Doctoral Dissertation

Managing Douglas-fir in Central European Forests

submitted by

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Preface and list of papers

The current doctoral thesis was realized in cumulative form, consisting of the scientific publications as listed in the following:

Paper 1	Eberhard, B., & Hasenauer, H. (2018). Modeling Regeneration of Douglas fir forests in Central Europe. Austrian Journal of Forest Science, 135(1). https://www.forestscience.at/content/dam/holz/forest-science/2018/heft1/CB1801_Art3.pdf
Paper 2	Eberhard, B. R., Eckhart, T., & Hasenauer, H. (2021). Evaluating Strategies for the Management of Douglas-Fir in Central Europe. Forests, 12(8), 1040. DOI: 10.3390/f12081040
Paper 3	Eberhard, Benno, & Hasenauer, H. (2021). Tree marking versus tree selection by harvester operator: are there any differences in the development of thinned Norway spruce forests? International Journal of Forest Engineering, 1–11. DOI: 10.1080/14942119.2021.1909312

The papers in full text are available in the Appendix of this doctoral dissertation.

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Vienna, December 2021 Benno Eberhard

Abstract

It has become a common understanding of forest managers to adopt climate smart guidelines for the decision making, which includes the assumption of unfavourable environmental conditions for the tree growth over the upcoming decades. Such attitude implies the willingness to act on a strategic level in terms of anticipatively preparing the forests for the expected adverse scenarios. In this context, the current doctoral thesis deals with the idea that the introduction of the productive and drought-resistant non-native tree species Douglas-fir is a promising measure for a twofold aim, to ensure the forest resource production on desired levels, and to enhance the resistive as well as resilient strength of native forest communities. In order to provide forest managers with appropriate treatment guidelines, analyses on the growth characteristics as well as the growth responses to manifold kinds of silvicultural interventions are required. The present thesis concentrates on the evaluation of four respective aspects, i) the regenerative capacity, ii) the development of Douglas-fir cultivations on limestone, iii) the growth response to alterations in mixture form as well as thinning regime, and iv) the growth response to two different figures when performing the thinning, i.e. tree marking by forest manager and tree selection by harvester machine. Aspects i), iii), and iv) were realized by simulation. As simulation device the MOSES single tree growth simulator was engaged, by previously calibrating the integrated growth functions for Douglas-fir. The data used for the calibration process were collected in 30 Douglas-fir stands spread over entire central Europe, representing all kinds of age classes and site conditions. For the accomplishment of aspect ii) four Douglas-fir plantations were established on calcareous bedrock in lower Austria. The input data for aspect iv) came from a field experiment with the participation of forest managers and harvester machine operators in lower Austrian forest stands. Results suggest that Douglas-fir regenerates naturally in the majority of the executed simulation runs, but in the phase after establishment it comes under heavy pressure mainly due to beech and needs human support. The cultivation on limestone exhibits no remarkable failure rate during the first years of growth. Intermediary results in this context indicate that higher nutrient contents are unfavourable for the young trees. Simulations on management options show that a mono-species planting yields better results than a species-intermixing, and that the sensitivity of Douglas-fir to thinning variants is moderate, since numerous light interventions as well as few heavy removals lead to similar results. According to respective simulations, the performance of stands after tree marking is not significantly different from the development after the one-work-step variant, where the harvester driver does the tree selection by himself.

Keywords: Douglas-fir, model calibration, treatment scenarios, silvicultural guidelines

Kurzfassung

Im forstlichen Kontext ist es zu einer Grundsatzhaltung geworden, Entscheidungen immer auch mit Blick auf die Klimaveränderung zu treffen. Das bedeutet konkret, von sich verschlechternden Rahmenbedingungen für Waldwachstum auszugehen und strategische Grundsätze einzubeziehen, um die Wälder auf die zu erwartenden Herausforderungen vorzubereiten. Die vorliegende Dissertation geht von der Überzeugung aus, dass es in diesem Zusammenhang sinnvoll ist, die hoch produktive und trockenresistente nicht-heimische Baumart Douglasie zu verwenden, erstens um den Holzbedarf abzudecken, und zweitens, um die Resistenz und Resilienz der bestehenden Wälder zu stärken. Dies macht es notwendig, Waldbewirtschafter mit tauglichen Richtlinien für die Douglasienbewirtschaftung auszustatten, was voraussetzt, deren Wuchsverhalten und Reaktion auf verschiedene Eingriffsmaßnahmen zu untersuchen. Diese Arbeit konzentriert sich dabei auf folgende Aspekte, i) das Naturverjüngungsvermögen, ii) die Entwicklung von Douglasienkulturen auf Kalk, iii) den Einfluss verschiedener Mischungsformen und Durchforstungsregime auf das Wuchsverhalten, und iv) die Fragestellung, ob sich Durchforstungen mit und ohne vorhergehende Försterauszeige unterschiedlich auf die Entwicklung auswirken. Die Forschungsaspekte i), iii) und iv) wurden durch Simulation erarbeitet. Als Wuchssimulator wurde die Software MOSES verwendet, für die die Baumart Douglasie auf Basis der Datenerhebung in 30 Douglasienbeständen Mitteleuropas kalibriert wurde. Für die Erarbeitung von Forschungsaspekt ii) wurden vier Douglasienkulturen in den niederösterreichischen Kalkalpen angelegt. Die Eingangsdaten für die Analyse von Forschungsaspekt iv) kamen von einem Durchforstungsexperiment mit Förstern und Harvestermaschinen im niederösterreichischen Waldviertel. Die Simulationsergebnisse zeigen, dass sich die Douglasie mehrheitlich erfolgreich verjüngt, jedoch in der darauffolgenden Anwuchsphase unter schweren Konkurrenzdruck vor allem durch die Buche gerät. Die Douglasienkulturen auf Kalk zeigen keine auffälligen Ausfallsraten in den ersten Entwicklungsjahren. Weiters zeigt sich in diesem Zusammenhang, dass sich höhere Nährstoffgehalte nachteilig auf die Vitalität der jungen Pflanzen auswirken. Simulationen von Managementvarianten legen nahe, dass in Mischung mit Buche und Fichte eine gruppenweise Pflanzung für die Douglasie besser ist als eine einzelstammweise Anordnung. Weiters wird deutlich, dass hinsichtlich Stabilität und Produktivität unterschiedliche Durchforstungsregime zu ähnlichen Ergebnissen führen. Und schließlich machen die Simulationen deutlich, dass sich die Entwicklungsverläufe von Beständen nach Försterauszeige nicht signifikant von solchen nach Harvesterfahrer-Auswahl unterscheiden.

Schlagwörter: Douglasie, Modellkalibrierung, Managementszenarien, Bewirtschaftungsgrundsätze

Contents

1 Introduction

Climate change is expected to modify the European forests in many regards such as tree species distribution, biodiversity, regeneration capacity, forest structure, productivity and growing stock (Duveneck and Scheller, 2016). Under such conditions, it has become a common understanding in forestry to consider the appropriate reaction to climate change as an integral part of management. Still, the day-to-day work on an operational level consists in keeping the traditional ecosystem services of forests on the desired level, the timber production, the protection of infrastructure, the supply of enjoyable water, the conservation of biodiversity and wildlife habitat, and the provision of aesthetic values for recreation. However, this business-as-usual attitude is increasingly overwhelmed by the principal uncertainty how to protect the forests themselves in the long run, by anticipating scenarios of unfavourable environmental conditions. This challenge has become a kind of common orientation in forestry on a strategic level (sensu Millar et al., 2007). Such circumstances necessitate a twofold response of the forest managers, to comply with the tasks from the day-to-day and to embrace the future shortcomings.

It is forecasted that tree species will accomplish a shift towards north (Chakraborty et al., 2021; Dyderski et al., 2018). This means that tree species adapted to warmer regions will migrate to higher latitudes at rising temperatures and will replace the existing set of tree species. From the central European perspective this entails a noticeable reduction of economically interesting coniferous species such as Norway spruce (Hanewinkel et al., 2013). Among the first forest types that are predicted to decline (Vitali et al., 2018, 2017) are the human-induced Norway spruce stands on sites in the lowlands where the vegetation naturally is composed by broadleaves. These are the so-called secondary conifer forests. In addition, there is evidence for a tendency of the policy makers to subtract about 10% of the forested land all over the European Union to commercial management, and to attribute these stands to natural reserves and other conservation areas, with no or very restricted commercial orientation (EU-Commission, 2020; Isermeyer et al., 2020). On the other hand, we observe a societal development that leads to a steadily increasing hunger for raw materials, with a clear preference for resources coming from sustainable production such as timber. Especially the paper industry is predicted to suffer from severe shortages due to this trajectory. Both above-mentioned aspects, the shift from conifers to broadleaves as well as the reduction of the forest areas with commercial orientation, will affect the available resources of a sector that substantially depends on pulp extracted from conifer trees. At the same time it is forecasted that the social need for paper and paper-related goods out of all forestry-based products will increase the most (Elias and Boucher, 2014).

Available strategies how to face global warming draw upon two principal concepts, adaptation and mitigation (Galatowitsch et al., 2009; Millar et al., 2007; Sánchez-Pinillos et al., 2019; St-Laurent et al., 2021; Thompson et al., 2009). The adaptation approach aims at preparing the forests for detrimental events such as long-lasting droughts, windblows, heavy snowpacks, frosts, wildfires, pathogens, and insects, while mitigation aims at reducing the expected harmful impacts, for instance by reducing the CO2 emissions. The adaptation option contains three types of climate-smart attitudes i) resistance ii) resilience iii) response/transformation. Resistance aims at enhancing the strength of a forest to withstand to the expected harmful events. Concrete measures encompass silvicultural interventions such as thinning leading to a boost of the diameter growth and a stability increase, slash removal for reducing forest fires, the generation of unstocked stripes on the edges as barriers against fires, pests and insects, resistance breeding resulting in the generation of robust populations etc. In total, the resistance concept focuses on the situation before the expected calamity. In contrast, the resilience approach starts from the assumption that a catastrophic event has already taken place. It aims at taking measures to support the ecosystem to recover and to return to the original status. Concrete measures include the amelioration of site conditions by fertilizing, the use of appropriate plants and seeds, the generation of buffers for triggering the restart of stand development, the enhancement of forest connectivity and reduction of fragmentation, the maintenance of a permanent regeneration layer etc.

In total, resistance as well as resilience aim at the conservation of the existing ecosystem. Instead, the response/transformation approach intends to change the existing conditions anticipatively, and to build up a new ecosystem which is considered better adapted to the expected circumstances. Possible measures concentrate on the introduction of new tree species, by assisting migration of native species, or by introducing non-native species as a stabilizing component for the future.

This study deals with the use of the non-native tree species Douglas-fir in central European forests, as a response measure to climate change, as explained before. Douglas-fir in this context is considered a promising element with the potential of making the forest ecosystems more robust and of reducing the risk of timber shortages.

Doulas-fir (*Pseudotsuga menziesii* [Mirbel] Franko) originates from northwest America, the so-called Pacific Northwest. It includes two varieties, the coastal variant (*Pseudotsuga menziesii var. viridis*), and the inland variant (*Pseudotsuga menziesii var. glauca*). Coastal Douglas-fir colonizes an elongated rectangular strip facing from North to South with 200 to 250 km in width and 2.200 km in length, which incorporates two mountain ranges, the Cascades (in British Columbia, Washington, and Oregon) and the Sierra Nevada (in California). Within this distribution range two regions can be differentiated, the Coast Range and the Cascade Range. The climate condition in this region is maritime semi-humid with annual precipitation up to 3500 mm, with mild winters, cool and dry summers, long vegetation periods and short frost occurrences (Aas, 2008; Hermann and Lavender, 1990; Höltermann et al., 2008). Coastal Douglas-fir therefore is characterized as a nemoral tree species, growing in so-called coniferous temperate rain forests. The inland variety grows on the Rocky Mountains, heading from British Columbia to Southeast over 4.500 km with foothills ending up in Mexico. This variety is less productive than the coastal type, and much more vulnerable to Swiss needle cast (*Rhabdocline pseudotsugae)* (Hermann and Lavender, 1990), which is a serious problem for stands in the biomass accumulation phase. Therefore, it is not relevant for European forestry.

Douglas-fir has been introduced in Europe about 160 years ago. Except north Europe, it is present all over Europe covering approx. 800.000 ha (Pötzelsberger, 2018; Pötzelsberger et al., 2020). Most of these forests are located in central west Europe, covering 400.000 ha in France, 200.000 ha in Germany and 60.000 ha in UK (FOREST EUROPE, 2015: State of Europe´s Forests 2015). Since it exhibits less susceptibility to heat as well as prolonged drought periods (Vor et al., 2015), it is a promising element of adaptation strategies that aim at making Europe´s forests fit for climate change.

In the context of using Douglas-fir outside its natural range there is a set of topics dominating the scientific as well as public awareness. Main aspects are i) genetic diversity and provenance (Chakraborty et al., 2016; Hintsteiner et al., 2018; Kölling, 2008; Konnert and Ruetz, 2006; van Loo et al., 2015), ii) the identification of suitable site conditions, iii) the compatibility with the native ecosystem with a special interest on invasiveness (Goßner and Ammer, 2006; Goßner and Simon, 2002; Höltermann et al., 2008; Knoerzer, 1999; Schmid et al., 2014; Wohlgemuth et al., 2021), and iv) wood properties and merchantability (Hein et al., 2008; Rais et al., 2014; Todaro and Macchioni, 2011; Weiskittel et al., 2007, 2006).

These research aspects provided the thematic framework for a Douglas-fir project (CCDouglas II) established by the Institute of Silviculture of the BOKU University of Natural Resources in Vienna (2013 - 2018). It involved three central European administrative units and 24 forest companies, altogether disposing of long tradition in the Douglas-fir cultivation. The main questions were i) what are the appropriate provenances for central Europe? ii) what are suitable site and soil conditions? iii) does the tree species regenerate well, what is the growth in competition with tree species from the native range, what are promising treatment strategies? Question i) aimed at analysing the genetic structure of Douglas-fir stands in Central Europe (Eckhart et al., 2017; Hintsteiner et al., 2018; Neophytou et al., 2020; van Loo et al., 2019, 2015). For this investigation 67 populations from Central European forests were used and compared with 28 reference populations from the native range. Question ii) focused on the impact of the site conditions on the productivity of the stands (Eckhart et al. 2019, 2014). On that basis occurred a mapping of growth potentials of Douglas-fir in Germany and Austria (Eckhart et al., 2019). Fürstenberg (2020) demonstrated for the Austrian growth region *Waldviertel*, which is extremely favourable for Norway spruce, that not only on poor sites but also on rich sites Douglas-fir is more productive than Norway spruce.

The research interest of the present study was developed in the framework of the mentioned project and concentrates on the question how to manage Douglas-fir stands properly. As it can be expected, most of the expertise on this regard has accumulated in the native range, the northwest America. And so, many silvicultural guidelines from this region are in place (Briggs, 2007; Curtis et al., 1998; Reukema, 1975; Talbert and Marshall, 2005; Worthington and Staebler, 1961). It is obvious that the growth conditions in the native range differ from the transfer destination, in climatic, geological, and geomorphological regards, as well as in the treatment history. In Europe, by drawing on knowledge since introduction (150 years) most of the investigations originate from France and Germany (Angelier, 2007; Angelier et al., 2004; Bailly and Dechamps, 1997; Bastien et al., 2013; Ehring and Kohnle, 2010; Kenk and Hradetzky, 1984; Klädtke et al., 2012; Kohnle et al., 2021; Pretzsch and Spellmann, 1994; Spiecker et al., 2019).

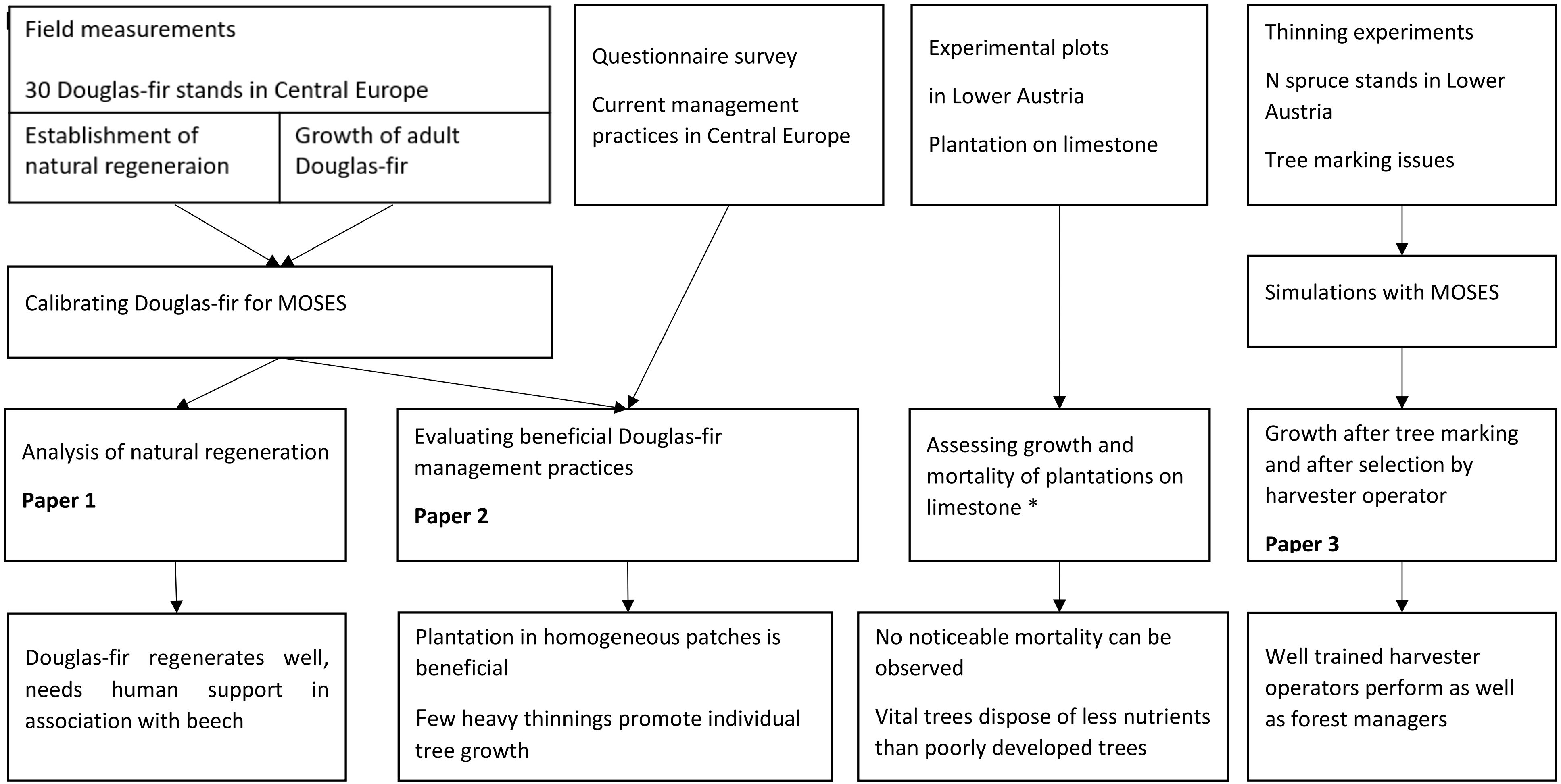
The thesis deals with four main aspects i) the natural regeneration dynamics ii) the development of Douglas-fir plantations on alkaline sites iii) the reaction of the tree species to different silvicultural treatment measures, and iv) the facilitation of thinning operations. Thus, the research questions of the doctoral thesis are:

1. Does Douglas-fir regenerate successfully?
2. What is the growth of Douglas-fir plantations on limestone?
3. What are promising management scenarios for Douglas-fir?
4. Is it reasonable to skip the work step of tree marking in context of thinning operations?

Aspects i), iii) and iv) were elaborated by modelling. As modelling software we used the growth simulator MOSES (Hasenauer, 1994; Thurnher et al., 2017). Since this tool was not prepared for our tree species, we calibrated the integrated growth functions for Douglas-fir, based on data coming from 30 Douglas-fir stands in central Europe. For aspect ii) an on-site experiment was conducted and realized in the northern calcareous alps of Lower Austria. For aspect iii) we took the existing central European management procedures as reference values for the simulation of alternative scenarios. For that purpose, a survey was distributed to forest companies all over the region. Aspect iv) aimed at facilitating the thinning operations. When it comes to thinning, it is a usual practice to do the tree selection in advance, so that a harvester operator can concentrate on the removal. We were interested in the question, if there is a difference if assigning the selective work to the harvester operator himself. For this purpose, we did thinning experiments in Lower Austria with forest managers and harvester machines, and implemented the data in the simulator for diagnosing the further development of the thinned stands. In the framework of this doctoral thesis, no Douglas-fir stands were available for this task. Therefore, we relocated the experiment to Norway spruce.

The key aspects and the workflow of the doctoral thesis are depicted in Figure 1 (next page).

Figure 1 Workflow of the doctoral thesis



* (Ammerer et al., 2021), bachelor thesis with supervision by B. Eberhard and H. Hasenauer

2 Materials and Methods

2.1 Model calibration

As essential preparative step of this thesis, the growth simulator MOSES (MOdellingStand rESponse) has been calibrated for Douglas-fir (paper 1 and paper 2). MOSES was generated for the simulation of management scenarios within even and uneven-aged pure or mixed species stands. The calculation unit is the single tree. On that basis the stand-wise growth-and-yield-parameters such as stem volume, basal area, stem number, mean height, mean diameter, HD-value (height-diameter ratio) of the mean stem, and dominant height, are determined. The model runs on the potential-modifier principle, which includes two steps, the calculation of potential increment rates for both tree height as well as tree diameter, and a modification of the potential values according to inter-tree competition. The model simulates the growth in growth periods of five years each.

Since it is based on the potential-modifier principle, the potential tree height represents an essential value for all further calculations. The potential tree height depends on the site conditions as expressed by site index functions that describe the development of the dominant height of a stand. For our study, we re-calibrated the function for Douglas-fir, based on Douglas-fir site growth data published by (Bergel, 1985) and (Eckmüllner, 2015). The applied model is the Richard growth function (Mitscherlich, 1919) with the following form:

$$\mathrm{DH} = \mathrm{a} * \left(1 - \mathrm{e}^{-\mathrm{b}*\mathrm{t}}\right)^{\mathrm{c}} \qquad 1)$$

DH is dominant height, *t* is stand age, *a, b* and *c* are coefficients.

The potential tree height is the starting value for the effective height and diameter of a tree as well as the height to life crown base as a measure for competition (Hasenauer, 1997). The respective equations have the following form:

$$\mathrm{ih} = \mathrm{ih}_{pot} * \mathrm{cr}^{\mathrm{c}_0} * (1 - \mathrm{e}^{\frac{\mathrm{c}_1}{\mathrm{cicut}*(1+\mathrm{c}_2*(\mathrm{ci}-\mathrm{cicut}))}}) \qquad \textit{Height increment (m)} \qquad 2)$$

$$\mathrm{id} = \mathrm{id}_{pot} * \mathrm{cr}^{\mathrm{c}_0} * (1 - \mathrm{e}^{\frac{\mathrm{c}_1}{\mathrm{cicut}*(1+\mathrm{c}_2*(\mathrm{ci}-\mathrm{cicut}))}}) \qquad \textit{Diameter increment (cm)} \qquad 3)$$

$$\Delta\mathrm{Hlc} = \mathrm{c}_0\mathrm{h}^{\mathrm{c}_1} * \mathrm{e}^{\mathrm{c}_2*\sqrt{\mathrm{cr}}+\frac{\mathrm{c}_3}{\mathrm{cicut}}+\mathrm{c}_4*\mathrm{DBH}} \qquad \textit{Change of height to life crown (m)} \qquad 4)$$

ih refers to the height increment model, *id* the diameter increment model and *Δhlc* to the change of life crown base. With *dbh* the breast height diameter, *h* the tree height, *ihpot* the potential increment, *cr* the crown ratio, *ci* and *cicut* the competition index at the beginning and end of the growth period, respectively.

In addition, our growth simulator includes a regeneration tool (Golser and Hasenauer, 1997; Hasenauer and Kindermann, 2006), that likewise has been calibrated for Douglas-fir in the framework of this thesis. It consists of three basic functions for i) the regeneration probability/density (equation

5) ii) the competition (equation 6) and iii) the height growth (equation 7) of juvenile trees. The functions have the following form:

$$p_{BA} = \frac{1}{1 + e^{-1\bullet(a*konk+b\bullet dbh_{max}+c_{Hum})}} \qquad \textit{Regeneration probability} \qquad 5)$$

$$konk = \frac{\sum((a*mdbh)^{b}\bullet n_{rep}\bullet c)}{10000} \qquad \textit{Competition measure} \qquad 6)$$

$$\mathrm{ih} = \mathrm{ih}_{\mathrm{pot}} \bullet \left(1 - \mathrm{e}^{\frac{-1}{\mathrm{a\bullet CCF+b\bullet nTaller}}+\mathrm{c\bullet SUMD}}\right) \qquad \textit{Juvenile height increment (m)} \qquad 7)$$

$$SUMD = \left(\sum\nolimits_{n=1}^{N_d} \frac{1}{DIST_i} \bullet \frac{2DH}{N_d}\right) - 1 \qquad \textit{Sum of distances} \qquad 8)$$

p_{BA} is the probability of Douglas fir regeneration establishment, *konk* a competition measure, dbh_{max} the maximum diameter at breast height, *Hum* the humus type, *a, b, c* as parameter estimates, n_{rep} the number of stems per ha represented by each tree within a sample plot, *mdbh* a proxy for the crown area of a tree, ih the 5-year height increment, ih_{pot} the potential 5-year height increment derived from site index functions, *CCF* the Crown Competition Factor according to Krajicek et al. (1961), *nTaller* the number of trees taller than the subject tree, as a competition measure, *SUMD* the compensation factor of edge effected incidence of light, *Nd* the number of directions, *DIST* the distance to the stand edge, and *DH* the dominant height of the stand.

For the validation of the calibrated functions, a validation dataset independent of the calibration data was taken. As accuracy measures the residuals between predicted and observed values were calculated and assessed by the following three intervals, the confidence interval (CI, equation 9), the prediction interval (PI, equation 10) and the tolerance interval (TI, equation 11) (Reynolds, 1984):

$$CI = \overline{D} \pm \frac{S_D}{\sqrt{n}} \bullet t_{1-\frac{\alpha}{2},n-1} \qquad 9)$$

$$PI = \overline{D} \pm S_D \bullet \sqrt{1 + \frac{1}{n}} \bullet t_{1-\frac{\alpha}{2},n-1} \qquad 10)$$

$$TI = \overline{D} \pm S_D \bullet g_{1-\gamma,n,1-\alpha} \qquad 11)$$

$\overline{D}$ is the mean of the differences, S_D the standard deviation of the differences, *n* the sample size and *t* the 1-α/2 quantile of the t-distribution with n-1 degrees of freedom. The tolerance factor g (1-γ, 1-α) for the normal distribution accounting for the probability that (1-γ) 100% of the distribution D is within a probability of 1-α can easily be obtained from statistical tables (e.g. Sachs, 1999).

2.2 Data

The data for model calibration and validation came from 30 Douglas-fir stands in Austria and Germany. The stands were established and firstly surveyed between 2012 and 2014 and re-measured between 2017 and 2019. This way for each measured tree we registered the five-year growth needed for the model calibration. Out of the 30 experimental trials, 17 stands were used for model calibration, and 13 stands for model validation. Figure 2 displays the locations of the 30 surveyed stands and provides an illustration of one of these stands, and Table 1 gives a summary-statistics of the available plot data.

Figure 2 Locations of the Douglas-fir experimental plots used for model calibration and validation (left), and one of the surveyed stands (right).

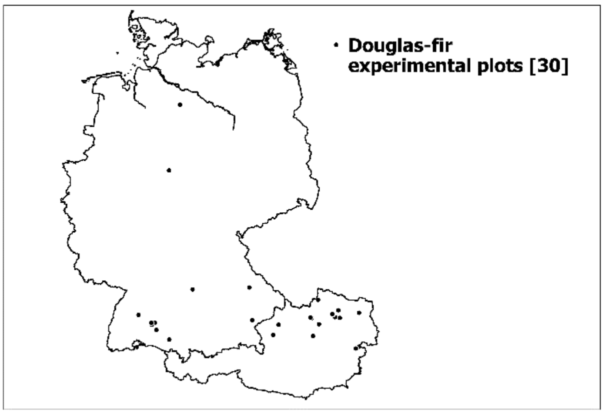
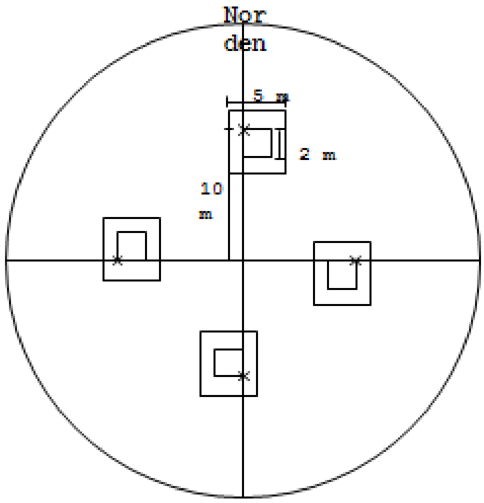


Table 1 Stand- and site-specific information on the recorded 30 Douglas-fir stands, with stand age, N the stem number, DH the dominant tree height, Dq the mean breast height diameter, V the stem volume, Elev the elevation above sea level, Annual Temp. the mean annual temperature, and Annual Precip. the annual precipitation. Stands 1-3, 6-8, 11-20 and 29 provide the calibration data (total 17 stands). The remaining 13 stands were established 2013/14 and re-measured 2018/19 and were used for validation.

Stand	Age	N/ha	DH (m)	Dq (cm)	V/ha (m³)	Elev (m)	Annual Temp. (°C)	Annual Precip. (mm)	Geology
1	90	136	35	52	324	290	9.9	600	Loess
2	84	164	43	62	720	460	9.6	720	Boulders in a sand-loam matrix
3	82	211	43	57	721	560	9.1	790	Mica schist, quartz phyllonite
4	40	399	23	32	278	520	9.3	770	Muscovite gneiss
5	38	558	24	32	371	360	9.5	650	Sand and argillaceous marl
6	52	188	27	39	223	370	9.1	570	Granulite
7	108	61	32	62	219	400	9.0	580	Granulite
8	58	748	33	39	822	430	9.1	640	Granulite
9	43	306	31	39	474	440	8.9	620	Magmatized granite-gneiss
10	42	285	29	39	386	410	9.0	610	Paragneis
11	70	165	39	64	595	330	9.4	960	Rubble
12	121	247	39	59	863	530	7.9	710	Granite
13	110	160	53	81	1317	820	7.1	2100	Carbonate-free, fine sandstone
14	109	76	50	82	740	640	8.0	900	Granite
15	105	108	53	77	829	660	7.9	910	Granite
16	104	207	50	73	821	590	8.3	890	Granite
17	54	324	33	50	650	660	8.1	1110	Gravel in sand matrix, fluvial
18	95	221	43	67	821	810	7.7	1450	Sandstone calcareous marl
19	100	226	48	67	1199	480	8.8	960	Silt, clayey-sandy, often gravelly
20	72	360	37	53	695	680	7.3	900	Biotite-granite
21	58	221	39	52	627	480	8.6	780	Impact breccia
22	62	350	39	49	749	670	8.2	1120	Glacial till, silt, sand, gravel
23	109	146	50	78	1158	660	7.9	870	Gravel, silt, clay, often stones
24	40	544	22	32	245	700	7.7	900	Limestone, dolomite
25	41	612	23	32	391	700	7.8	890	Corallian limestone
26	60	298	37	51	673	890	7.0	1050	Limestone, dolomite
27	51	366	34	41	453	450	9.1	970	Limestone, dolomite
28	50	279	32	48	579	520	8.8	1010	Dolomite
29	53	594	32	30	465	290	9.9	600	Variegated sandstone
30	37	910	28	31	873	460	9.6	720	Variegated sandstone

The data collection was done by a fixed sample plot with diameter 40 m, applying a hierarchical structure with three layers, (1) the overstory trees with dbh > 10 cm, (2) the saplings > 1.3 m in height and ≤ 10 cm in dbh, and (3) the regeneration layer with seedlings ≤ 1.3 m in height. Figure 3 gives an illustration of the sampling layout (for further sampling details see paper 1 and paper 2).

Figure 3 Sampling layout for the data collection. The sampled overstory trees were collected by a fixed sample plot, the saplings by four squares with length 5 m, and the seedlings by four squares with length 2 m, with the arrangement of the squares as depicted below.



2.2.1 Natural regeneration

The regeneration data came from 28 stands (stands 1-28 from Table 1). The trees in the regeneration layer were classified first into three species categories, Douglas-fir, other broadleaves (mainly beech), and other conifers (mainly Norway spruce), and second in two growth classes, seedlings and saplings, as depicted in Figure 3 (for more detailed information on the sampling procedure please see paper 1). Table 2 contains the hectare values for the resulting six categories, plus the parameters (maximum dbh on a respective plot, humus type) needed for the calibration of equations 5) and 6).

Table 2 Number of trees (N) in the regeneration layer of 28 stands. D is Douglas fir, Co Other conifers, Br is Other broadleaves, Re is regeneration (≤ 1.3 m in height), IL is the intermediate sapling layer (> 1.3 m in height and ≤ 10 cm in dbh), dbh_{max} is the maximum diameter of all trees, konk is the competition index (dimensionless) according to equation (6), Hum is the humus type, Mull is mull, Mod is decay, MuMo is mull-like decay, "-" indicates that no adult tree was on the plot.

Plot Nr.	N_{Re_D} (N/ha)	N_{IL_D} (N/ha)	dbh_{max_D} (cm)	N_{Re_Co} (N/ha)	N_{IL_Co} (N/ha)	dbh_{max_Co} (cm)	N_{Re_Br} (N/ha)	N_{IL_Br} (N/ha)	dbh_{max_Br} (cm)	*konk*	*Hum*
1	0	0	68	0	0	59	0	0	-	1.5	Mull
2	0	0	69	0	0	-	10625	900	-	3.8	Mull
3	0	0	66	0	0	-	0	200	-	3.7	Mull
4	0	0	29	0	0	44	0	0	-	4.4	Mod
5	0	0	50	0	0	-	24375	0	23	4.6	Mod
6	59357	0	43	0	0	-	4375	0	-	1.9	Mull
7	1250	300	80	0	0	-	0	0	-	1.5	Mull
8	43125	0	52	1250	0	31	0	0	21	6.3	MuMo
9	0	0	43	0	0	-	0	0	-	3.8	Mod
10	6250	0	46	25000	0	-	625	0	-	2.6	MuMo
11	6875	100	73	17500	0	23	30625	500	-	5.5	Mull
12	5000	100	77	6250	300	-	1875	100	-	5.5	Mod
13	0	0	125	0	0	-	0	0	-	3.4	Mull
14	3750	0	96	0	200	64	0	700	-	3.1	Mull
15	1250	500	95	16250	1400	-	0	100	-	5.8	Mod
16	1250	200	99	8125	200	-	625	200	-	3.1	Mod
17	0	0	57	0	0	40	0	0	-	5.3	Mod
18	1875	100	91	11250	2200	-	18750	2800	44	7.5	Mull
19	0	0	91	625	100	-	0	0	-	4.4	Mull
20	37500	0	71	103125	0	-	625	0	-	6.3	MuMo
21	625	0	70	1250	0	44	31250	0	33	3.5	Mod
22	0	0	70	71250	600	59	625	1600	-	10.2	Mod
23	0	0	97	0	0	77	0	100	40	2.4	Mull
24	0	0	43	0	0	-	0	0	-	3.1	Mull
25	0	0	40	0	0	-	0	0	-	4.8	Mull
26	0	0	69	0	0	39	0	1000	-	4.3	Mull
27	0	0	54	0	200	-	3750	5700	23	4.9	Mull
28	0	0	55	0	0	-	625	700	-	3.4	Mull

2.2.2 Growth and mortality of plantations on limestone

This experiment (see Ammerer et al., 2021) took place in the middle of the calcareous alps of Lower Austria. The research interest focused on two influencing factors on the growth, the provenance, and the site conditions. Two provenances were tested, *Ashford-Elbe* and *Douglasie-Nordwestdeutschland*, and the variation in site conditions was covered by four experiment replicates on different locations. Table 3 provides a summary of the site conditions, and Figure 4 shows one of the experimental sites.

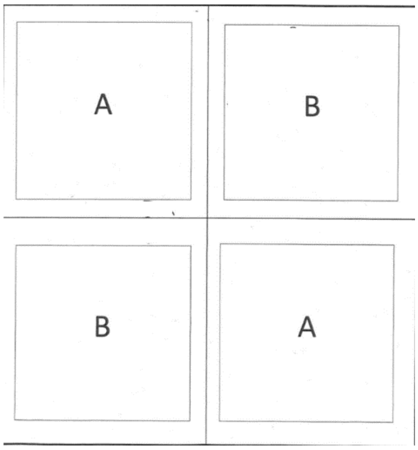
Table 3 Site characteristics of the four replicates/plots in the calcareous alps where the Douglas-fir plantations were established in the year 2017. W stands for west, E for east, S for south, pH is the pH-value.

Plot	Altitude (m)	Slope-exposition	Inclination (%)	pH (H_2O)	pH ($CaCl_2$)
Plot 1	770-850	W	57	7,05	6,74
Plot 2	860-920	E-SE	17	7,40	7,09
Plot 3	820-890	W	46	7,13	6,79
Plot 4	850-920	W	21	7,31	6,86

Figure 4 Experimental site of a Douglas-fir plantation on limestone, in the calcareous alps of Lower Austria.

The planting arrangement of the trees followed a block-design. Each of the replicates comprised four sub-plots with a buffer zone in between and two transversally shifted compartments for each of the provenances. As a result, the planting layout assumed the form as depicted in Figure 5.

Figure 5 Schematic representation of one of the four replicates of the Douglas-fir plantation on limestone, including four sub-sections, two for provenance Ashford (A), and two for provenance Douglasie-Nordwestdeutschland (B), respectively. Each of the couples of the sub-sample is placed in transverse orientation.



The applied spacing was two times two meters and as a general rule, the sides of the sub-squares were 20 meters in length. This way the trial should include 400 trees per replicate and 1.600 trees in total. Since not all sub-plots had the same size owing to geomorphological site constraints, the actual initial stem number after plantation in autumn 2017 was 1.538.

The data collection was done in spring of each year after plantation and comprised three measurements respected by this study, 2018, 2019 and 2020. It targeted two principal parameters, the height increment of the trees, and the number of trees gone due to mortality. In addition, in the year 2020 the nutrient content of the trees was assessed, based on a subsample of 80 trees that were evenly distributed to the four replicates. This sub-sample consisted of 40 vital and 40 poorly developed trees that in the context of this study were named as weak trees. In order to discriminate vital plants from the weak exemplars, the recording team adopted a classification based on visual impression. A tree disposing of a saturated green colour and a good growth of the shoots was classified as vital, while a pale shade of green and a miserable overall impression qualified a tree as weak. Please note that the nutrient content was not taken from the soil but from vegetative parts of the plants. For that purpose, the personnel took some living plant material (especially needles), stored it in bags and brought it to the laboratory of the National Research Centre of Forests (BFW) in Vienna. For the further analysis in the lab, the samples were dried at 105°C, the nutrient content was assessed and expressed as the percentage of the dry weight. The selection of the nutritive elements to be analysed referred to the (Bioindikatornetz, 2020). Table 4 provides a summary of the nutrient content of the sub sample of 80 trees.

Table 4 Summary of the nutrient content of the 80 young Douglas-fir trees according to vitality and provenance (20 trees for each category, A vital, A weak, B vital, B weak). The numbers represent the percentage of the dry weight. me is the mean value, min the minimum, max the maximum, and sd the standard deviation.

Nutrient	Vitality	Provenance A (Ashford) *(in % of dry weight)*				Provenance B (NW-Deutschland) *(in % of dry weight)*			
		me	*min*	*max*	*sd*	*me*	*min*	*max*	*sd*
N	Weak	1,4	1,0	1,7	0,3	1,4	1,0	1,6	0,2
	Vital	1,1	1,0	1,3	0,1	1,1	1,0	1,3	0,1
P	Weak	0,1	0,1	0,2	0,0	0,1	0,1	0,1	0,0
	Vital	0,1	0,1	0,1	0,0	0,1	0,1	0,1	0,0
K	Weak	0,8	0,7	0,9	0,1	0,6	0,4	0,7	0,2
	Vital	0,4	0,4	0,4	0,0	0,5	0,4	0,6	0,1
Ca	Weak	0,3	0,3	0,4	0,1	0,5	0,2	0,9	0,3
	Vital	0,2	0,2	0,3	0,1	0,2	0,2	0,3	0,0
Mg	Weak	0,2	0,2	0,3	0,0	0,3	0,2	0,3	0,0
	Vital	0,1	0,1	0,1	0,0	0,1	0,1	0,2	0,0

2.2.3 Beneficial management practices

The management issues for simulation were derived by analysing the state of the art of the current Douglas-fir management in central Europe, as collected by a survey (paper 2). The survey referred to basic components of the silvicultural work such as stand and site characteristics, tree species mixture, management strategies, and abiotic and biotic risks. It was developed within the framework of the above-mentioned project CCDouglas II. Table 5 gives a summary of the information collected by the survey.

Table 5 Summary of the survey on current Douglas-fir management practices in Central Europe. The information results from 19 forest companies and draws on 434 Douglas-fir stands.

Variety/ Provenance	Principal variety is coastal Douglas-fir (*Pseudotsuga menziesii var. viridis*), origins are Ashford Elbe, Darrington, Snoqualmie River, Trout Lake (USA), Centre Creek, Heffley Lake (Canada) (Hintsteiner et al., 2018).
Site and stand characteristics	Summer warm and dry climate in the Eastern part of Austria, oceanic climate in the Alpine foreland of Austria and low mountain range in Germany, astonished climate at the northern edge of the Alps; majority of stands at altitudes 650 m to 850 m, on silicate bedrock with soil depth 30 cm to 120 cm, 14% on limestone with soil depth <15 cm to 30 cm; water balance on silicate sites is moderately fresh to fresh, on limestone moderately dry; 76% of stands are aged < 20 years.
Species mixture	Principal associated species are Norway spruce, Common beech, silver fir, larch, Scots pine, sessile oak, maple tree; with stem number portion of Douglas-fir smaller 0.3 (44% of stands); greater 0.3 and smaller 0.5 (21%); greater 0.5 (14%).
Planting	Use of bare rooted plants is most common (73% of stands); planting operations performed by concave spade, whole driller (77%), or by planting in ditches (18%); spacing from 1.5m*2.5m to 5m*5m, most common being 1.8m*2m; most common initial stem number 2700/ha; portion of Douglas-fir on average is 30%; mixture form principally is tree by tree with Douglas-fir every 5 to 10 m, planting Douglas-fir in rows or groups is rare; planting largely occurs in spring; frequently reported problem is a fail of Douglas-fir due to insufficient initial stem number.
Natural regeneration	Establishment of Douglas-fir under the shelter of mature trees by opening up or group removal; insufficient opening up causes inadequate rooting and poor crown development; threats come from competitive vegetation, especially native tree species, and game damages.
Tending	Most commonly at top height 2m to 6m (74%), with stem number reduction by 30%; problems: sudden drop down of young Douglas-fir after release, as result of poorly developed roots and crowns (6%); problem is the spread of blackberry (*Rubus fruticosus*) after release.
Thinning	First thinning at top height 8 to 10m (83%), with removed volume 30-50m³/ha; subsequent interventions at intervals 5 to 10 years, with removed volume 50 – 120m³/ha; thinning method is crop tree selection (68%); mentioned problem is a degradation of the crown after thinning due to insufficient thinning and too late thinning (16%).
Debranching	Debranching at top height 8m to 10m (37%), at 12m to 15m (44%); debranched section of tree is between 5m and 10m (77%); reported problem is the big workload.

2.2.4 Growth after tree marking and after selection by harvester operator

This investigation (paper 3) used data coming from on-site experiments as starting values for the simulations. For this purpose, eight Norway spruce stands located in the northern part of Lower Austria close to the Czech border were selected. Since first and second thinning might be driven by different considerations by the two protagonists, forest manager and harvester operator, both types were included in the experiment. The stands were provided by four companies, and four harvester drivers and 16 foresters in total were involved. Table 6 provides information on site and stand characteristics, according to first and second thinned stands.

Table 6 Summary statistics of the eight selected Norway spruce forests for the tree marking experiment. Thin indicates first or second thinning, Elev is sea level, SI the Site Index according to (Lembcke et al., 1975; Persson, 1992; Schober, 1987), N/ha the stem number per hectare, BA the basal area/ha, Dq the quadratic mean breast height diameter, DH the dominant height according to Weise (1880), V/ha the volume per hectare, and H/D-ratio is the height – breast height diameter ratio.

Thin	*Stand*	*Elev (m)*	*Age*	*SI*	*N/ha*	*BA (m^2)*	*D (cm)*	*DH (m)*	*V/ha (m^3)*	*H/D-ratio*
1	1	850	40	35	2053	47	17	21	409	100
1	2	866	50	32	1422	57	22	23	561	92
1	4	920	27	44	1640	41	18	20	356	96
1	8	890	55	34	1537	74	25	26	802	91
2	3	925	40	45	1164	78	30	28	942	86
2	5	885	55	40	848	62	31	31	768	88
2	6	890	42	38	958	53	26	24	557	84
2	7	900	42	43	836	54	28	28	633	86

The data collection required two work steps, after the tree marking by forest managers (performed in autumn 2018), and after the harvester machine operations (executed in early spring 2019). For more detailed information on the procedure for data collection we refer to paper 3. By using removable ribbons for the tree marking, the two selection entries (first forest manager, after harvester driver) could be effectuated on identical stands, respectively. Figure 6 shows an exemplary stand with attached ribbons after the tree marking by the forest manager.

Figure 6 Stand ready for thinning with attached ribbons after the tree marking by the forest manager. In this case, the forest manager used red ribbons to designate trees for removal, and white ribbons for future crop trees.

On each stand several field plots were established, according to the size of the stands provided by the companies. In addition to thinning by forest manager and harvester driver, a random entry was generated by the simulation tool. Table 7 gives an overview on the field plots and the numbers of trees designated for removal by the three thinning variants.

Table 7 Description of the field plots (Plot) within the eight selected Norway spruce forests (Stand). Lplot and Wplot are the length and the width of the plots, N/plot is the total stem number, Fn the number of selected stems by the forest manager, Hn the selected and removed trees by the harvester operator, and Rn the randomly selected trees using the selection routine implemented in MOSES.

Stand	Plot	L_{plot} (m)	W_{plot} (m)	$N_{/plot}$	F_n	H_n	R_n	Stand	Plot	L_{plot} (m)	W_{plot} (m)	$N_{/plot}$	F_n	H_n	R_n
1	1	15	11	40	10	23	14	5	13	21	11	16	6	9	9
1	2	12	11	25	6	12	12	5	14	13	13	17	7	10	7
1	3	13	14	37	16	21	17	6	15	15	15	26	16	13	15
1	4	15	11	36	12	20	14	6	16	16	13	15	8	6	6
1	5	15	11	35	11	18	11	7	17	18	13	19	10	8	8
1	6	15	13	27	7	10	7	7	18	13	13	14	7	6	6
2	7	11	12	18	7	4	5	8	19	13	17	31	17	12	15
3	8	15	15	25	8	8	8	8	20	10	14	21	13	12	13
3	9	12	13	19	7	9	9	8	21	13	9	20	13	8	11
4	10	14	16	31	13	10	10								
4	11	12	12	21	10	11	11								
4	12	11	13	28	10	13	10								

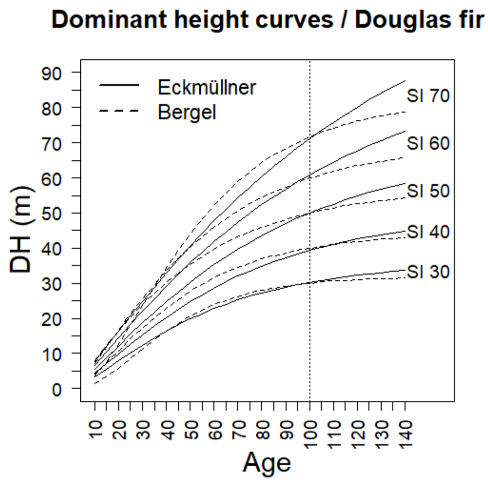
All statistical evaluations were done by using (R Core Team, 2019).

3 Results

3.1 Model calibration and validation

The calibration of MOSES for Douglas-fir refers to the regeneration sub-tool (paper 1), the dominant height function, and the growth functions for adult Douglas-fir (paper 2). The dominant height of stands, as explained above, represents an essential concept for the workflow of our simulator. Two yield tables, Bergel (1985) and Eckmüllner (2015), were tested for the calibration of the height curve function (equation 1). Figure 7 shows the height curve collectives according to stand age and site index, for both yield tables.

Figure 7 Dominant height curves of Douglas-fir according to the yield tables of (Bergel, 1985) and (Eckmüllner, 2015).



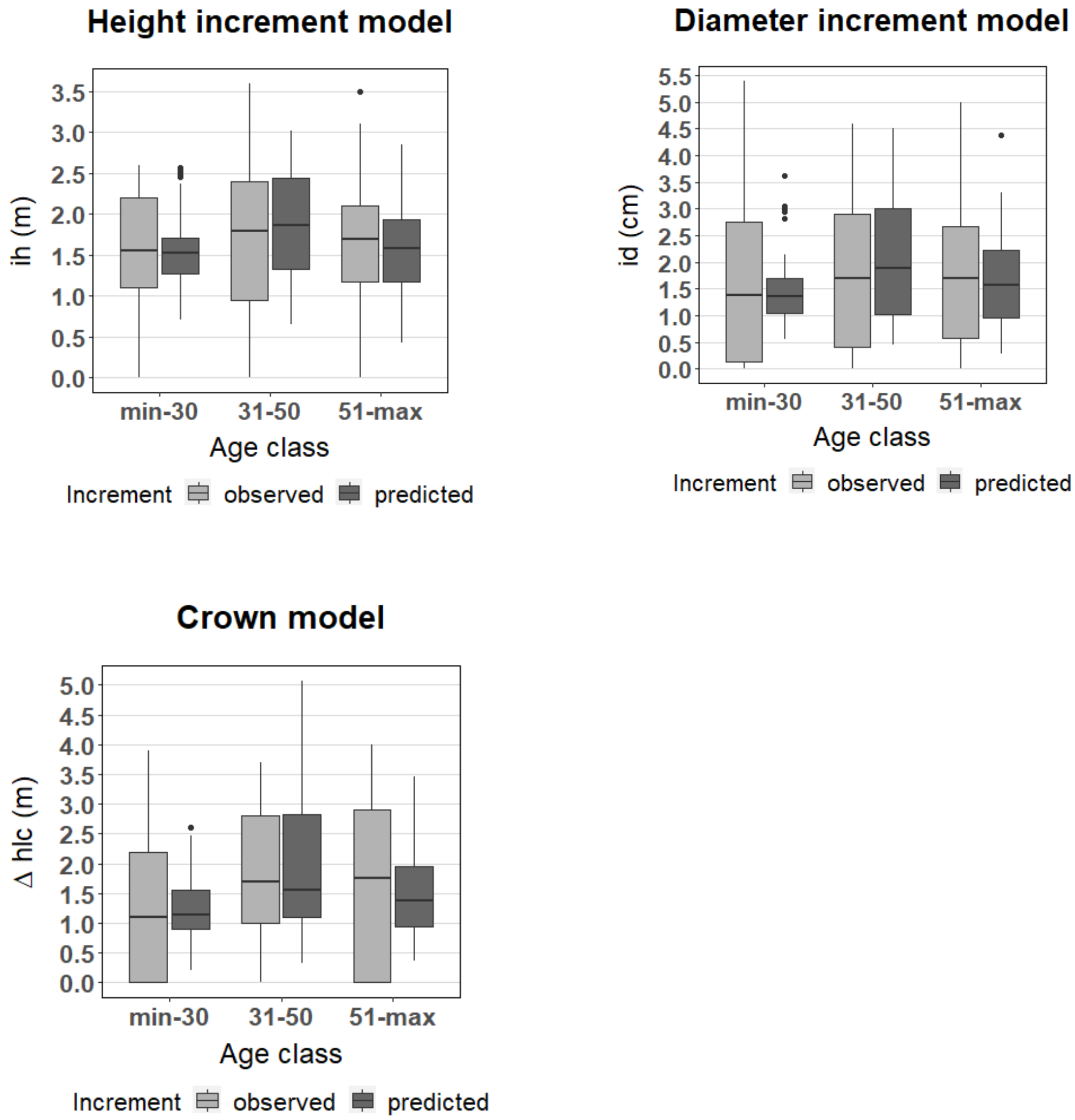
The Eckmüllner function was implemented in the simulator since the model validation thereby displayed higher accuracy. On that basis, the coefficient estimates for equation 2) (mature height growth), equation 3) (diameter growth), equation 4) (shift of height to life crown base), and equation 7) (juvenile height growth) were realized. Table 8 shows the results.

Table 8 Results of the coefficient estimates for the MOSES growth functions. With ih the height increment model, id the diameter increment model, Δhlc the model for change of height to life crown base, dbh the breast height diameter, h the tree height, i_{pot} the potential increment, cr the crown ratio, ci and cicut the competition index at the beginning and end of the growth period, CCF the Crown Competition Factor according to (Krajicek et al., 1961), NTaller the Number of trees taller than the subject tree, and SUMD the Sum of Distances as measure for edge effected incidence of light.

Increment model	**Coefficient**	**Estimates / significance level**
$\mathrm{ih} = \mathrm{ihpot} * \mathrm{cr}^{c_0} * (1 - e^{\frac{c_1}{\mathrm{cicut}*(1+c_2*(\mathrm{ci}-\mathrm{cicut}))}})$		
	c_0	0.174 *
Height increment model *ih*	c_1	-10.3 **
for adult trees	c_2	0.461
$\mathrm{id} = \mathrm{idpot} * \mathrm{cr}^{c_0} * (1 - e^{\frac{c_1}{\mathrm{cicut}*(1+c_2*(\mathrm{ci}-\mathrm{cicut}))}})$		
	c_0	0.562 **
dbh increment model *id*	c_1	-5.34 **
	c_2	0.116
$\Delta\mathrm{hlc} = c_0 h^{c_1} * e^{c_2*\sqrt{\mathrm{cr}}+\frac{c_3}{\mathrm{cicut}}+c_4*\mathrm{dbh}}$		
	c_0	0.00108
Dynamic crown model *Δhlc*	c_1	1.31 **
	c_2	6.37 **
	c_3	-0.604
	c_4	-0.0257 **
$\mathrm{ih} = \mathrm{ih}_{\mathrm{pot}} \bullet \left(1 - e^{\frac{-1}{a\bullet \mathrm{CCF}+b\bullet \mathrm{nTaller}}+c\bullet \mathrm{SUMD}}\right)$		
	c_0	0.05481 ***
Height increment model *ih*	c_1	0.12137
for juvenile trees	c_2	-0.04093 ***
Significance level: *** 0.001 ** 0.01 * 0.05		

When using the mentioned intervals as measures for accuracy, the confidence interval (CI, equation 9), the prediction interval (PI, equation 10), and the tolerance interval (TI, equations 11), it is essential that zero is included in the interval. The validation results for the calibrated functions are, in terms of the confidence interval (CI) as the most stringent out of the three accuracy measures: -0.063 m to 0.13 m (equation 2), -0.089 cm to 0.15 cm (equation 3), -0.21 m to 0.13 m (equation 4), -10.6 cm to 3.3 cm (equation 7). Thus, zero is complected by the interval in all cases, so that the validation in all cases was satisfying. For equations 2, 3, and 4 (growth functions for mature Douglas fir) the conformity between predictions (by calibrated models) and observations (validation dataset, see Table 1) reflects from Figure 8 where the mean values for both categories predicted and observed are shown (in relation to three age classes).

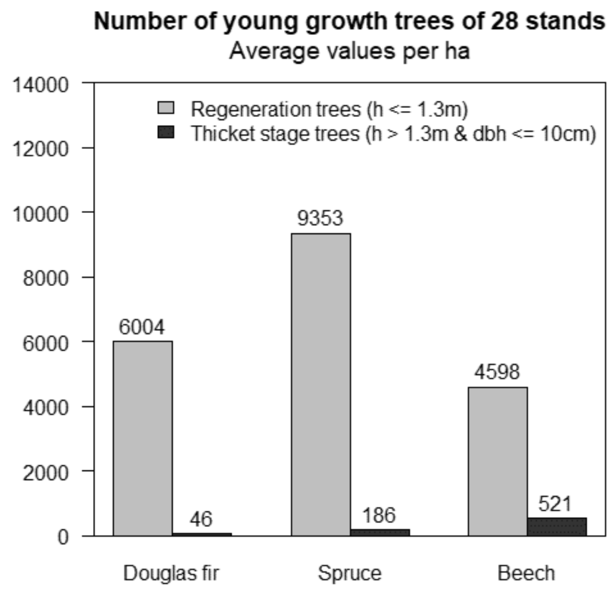
Figure 8 Predicted vs. observed five-year increments of the calibrated models for height increment (ih), diameter increment (id) and change of height to life crown base (Δ hlc), in relation to three age classes (until 30 years, from 31 to 50 years, from 51 years onwards).



3.2 Natural regeneration

Based on Table 2 that contains the regeneration occurrence (see also paper 1), the average tree number/ha (of all 28 stands) of Douglas-fir, other conifers (mainly Norway spruce) and other broadleaves (mainly beech), for both categories seedlings (height ≤ 1.3 m) and saplings (height > 1.3 m & dbh ≤ 10 cm), amounts to the numbers as depicted in Figure 9 (left). We see that Douglas-fir in the bottom layer is present with 6004 trees/ha, and in the medium layer with 46 trees/ha. When comparing this ratio with the respective numbers for Norway spruce, the probability for Norway spruce to enter the medium layer (186/9353) is 2.6 times higher than for Douglas-fir, and the probability for beech is 14 times higher than for Douglas-fir. This suggests that Douglas-fir at advanced growth comes under severe pressure mainly by beech.

Figure 9 Left: Average stem number/ha of Douglas-fir, other conifers (mainly Norway spruce), and other broadleaves (mainly beech) within the two differentiated regeneration layers (seedlings up to 1.3 m height, and saplings from 1.3 m height up to 10 cm dbh) on 28 Douglas-fir stands (Table 1). Right: One of the sampled stands, suggesting that Douglas-fir gradually comes under pressure by beech.



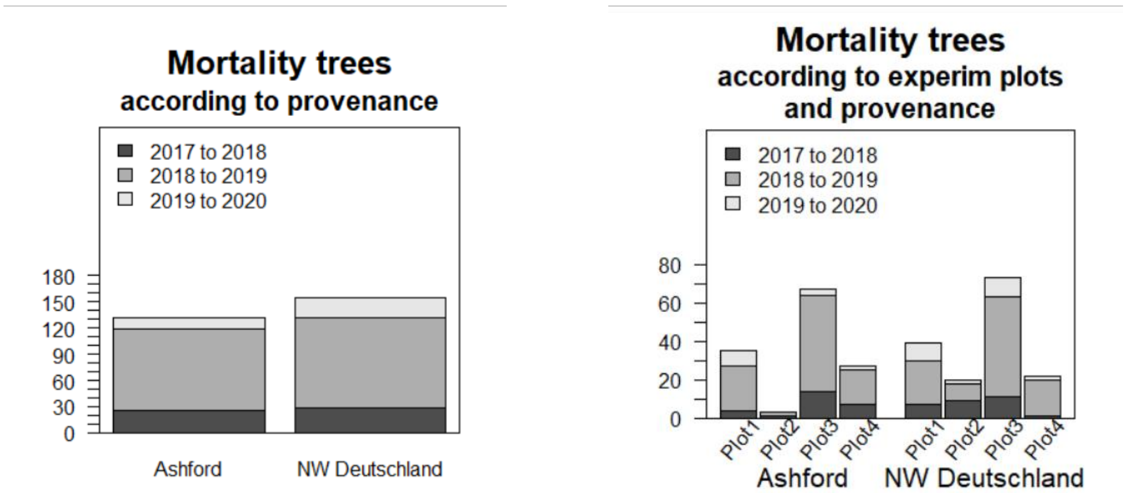
3.3 Growth and mortality of plantations on limestone

The here presented results for this study (for details see Ammerer et al., 2021) involve two categories i) mortality of the planted trees within the first three years after plantation, and ii) nutrient content of the trees. Since this experiment is still ongoing, the here presented results are considered intermediary.

3.3.1 Mortality

With a decrease of the total tree number from 1538 to 1234 (including all four replicates, see Table 3), the mortality rate amounts to 19%. Figure 10 shows the number of mortality trees for the single growth periods 2017-2018, 2018-2019, 2019-2020. The figure on the left shows the results according to the two provenances, and the figure on the right according to the four replicates, by integrating the two provenances.

Figure 10 Number of trees gone due to mortality between 2017 and 20120, for the two provenances and the four experimental sites. For visualization purposes, the plots on the right are also differentiated according to the provenances, but for the statistical assessment we might imagine the bars of both provenances as stacked one upon the other, respectively.



A Pearson´s χ²-Test (p=0.03487) shows that provenance NW Deutschland has a slightly higher mortality. The differences between the plots are clearly visible, which also reflects from the χ²-Test (p=9.447e-05).

3.3.2 Nutrient content

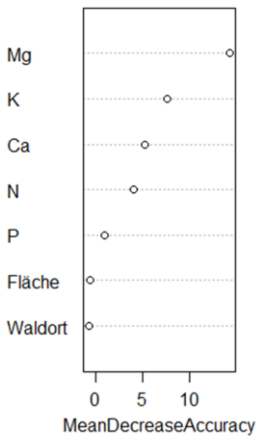
An overview on Table 4, providing a summary on the nutrient contents (nitrogen N, phosphorus P, potassium K, calcium Ca, and magnesium Mg) of the subsample of 80 trees, suggests that the vital exemplars contain less nutrients compared with the weak (poorly developed) ones. A pairwise Wilkoxon-test for this purpose confirms a significant difference for all cases (Table 9).

Table 9 Outcomes of the pairwise Wilcoxon-test on the nutrient content of weak and vital trees of the Douglas-fir plantation on limestone. The Wilcoxon-test is based on the vitality status (40 vital trees, 40 weak trees), regardless of the provenance.

N	p = 0.03179
P	p = 0.002483
K	p = 2.334e-07
Ca	p = 1.392e-08
Mg	p = 7.276e-12

An assessment by RandomForest (Breiman, 2001; Cutler et al., 2007) for all 80 trees makes evident that there is not only a significant relationship between the nutrients and the vitality status of the trees, but also a relation in terms of causality (expected error rate in further predictions with the generated RandomForest model of 8.75%). A further assessment by RandomForest on the impact of the single nutrients on vitality yields the result that Mg and K are of most relevance. E.g. when removing Mg in a subsequent RandomForest prediction run, the model accuracy would decrease by approx. 15% (see Figure 11).

Figure 11 Variable importance plot generated by the RandomForest algorithm, in order to test the influence of the nutrients on the vitality degree of the young Douglas-fir trees on limestone.



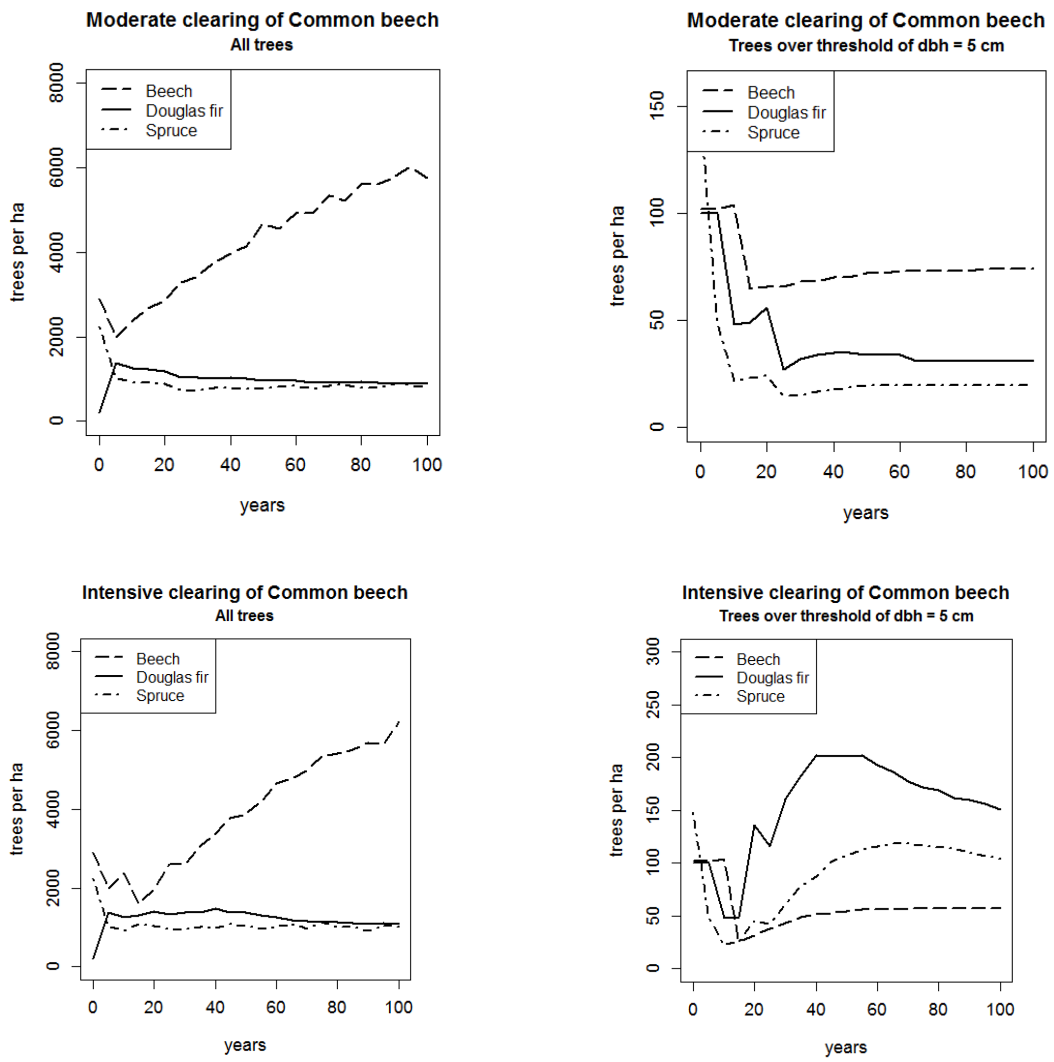
3.4 Beneficial management practices

In context of the evaluation of beneficial management guidelines for Douglas-fir stands (paper 2), the tasks for the simulations as derived from the survey (see Table 5) are: i) *Ensuring the natural regeneration ii) Planting options iii) Tending/Thinning strategies.*

3.4.1 Ensuring the natural regeneration

As explained above (chapter 3.2.) after the establishment phase Douglas-fir comes under competitive pressure mainly by beech. Useful remedy strategies were evaluated based on a sampled stand (stand 18 in Table 1). A detailed description of this stand and the assumed strategies (complecting moderate and heavy entries) are given in paper 1 and paper 2. The simulations (Figure 12) make clear that after a moderate removal of beech (top), Douglas-fir is inferior in the long run both in the regeneration layer (top left) as well as in the intermediate/top layer (top right). But after a heavy removal of beech (bottom), Douglas-fir, still being inferior in the regeneration layer (bottom left), achieves a sufficient superiority in the intermediate/top layer and remains the prevailing component on that stand (bottom right).

Figure 12 Growth of a Douglas-fir-beech-spruce stand after different measures for the release of Douglas-fir (moderate removals versus intensive removals of beech in favour of Douglas-fir) in context of tending and thinning, according to simulation. Apparently, Douglas-fir regeneration is less competitive than beech (top left, bottom left). Douglas-fir needs intensive human support for the long-term persistence (bottom right).

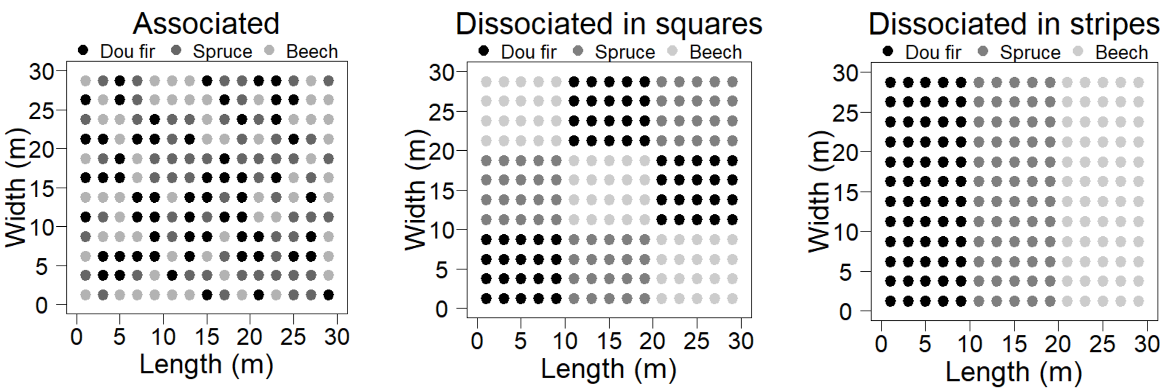


3.4.2 Planting options

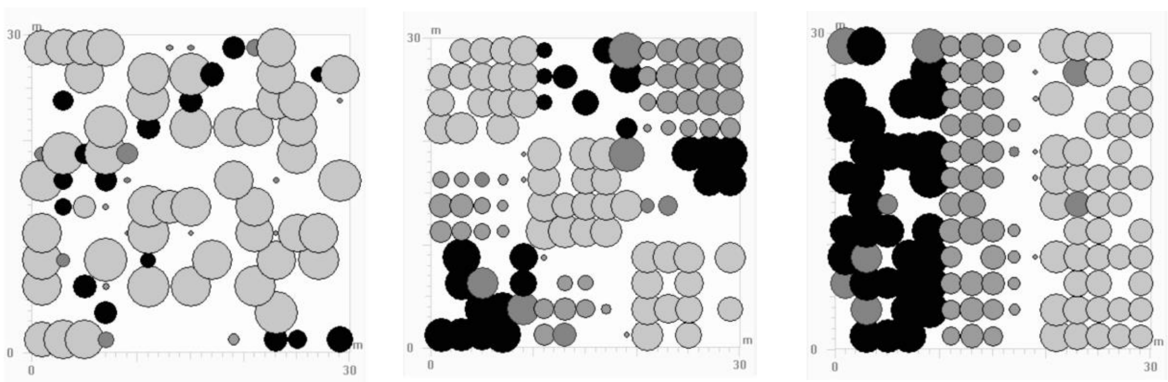
This analysis of a mixed plantation (Douglas-fir-beech-Norway spruce) concentrates on the question whether the mixture form should be tree by tree and intermixed, or in homogeneous patches with the single species growing separately from each other. The simulation starts from an artificially generated stand, assuming different planting layouts (for detailed descriptions see paper 2). An illustration of the assessed planting arrangements (top) and the corresponding simulation results (bottom) is given in Figure 13. Evidently, Douglas-fir (black dots) when intermixed with the associates, shows the poorest performance at the end of the simulation (bottom left), whereas in dissociation (bottom middle) and even more at enlargement of the planting compartments (bottom right) it displays a visibly enhanced performance.

Figure 13 Three different planting variants of Douglas-fir within mixed stands with common beech and Norway spruce. The figures depict the three plantation layouts (i) Random/Associated, (ii) Square/Dissociated, and (iii) Strip/Dissociated.

Initial stage



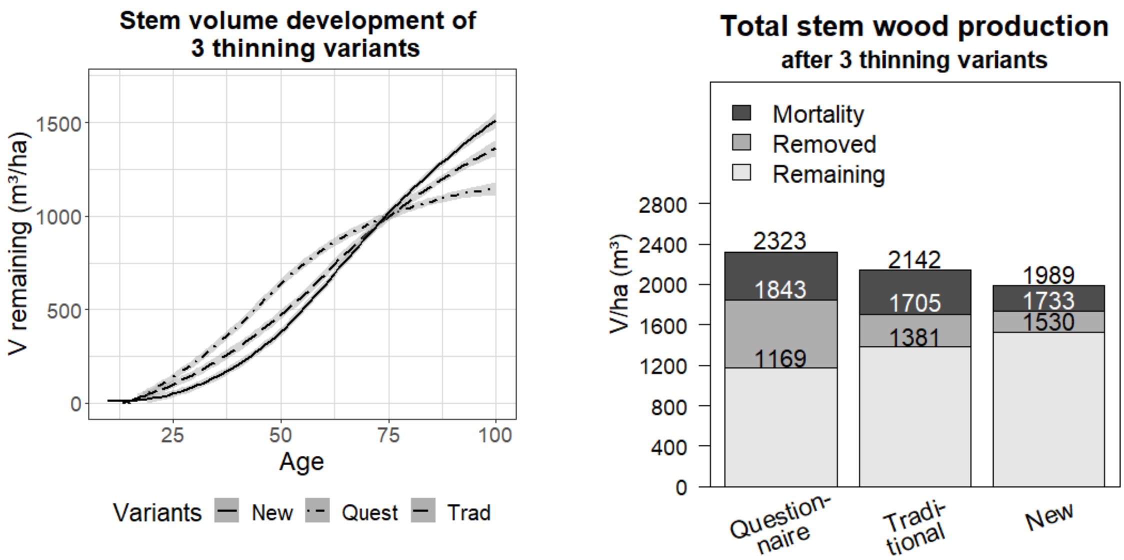
Final stage (after simulation)



3.4.3 Tending/Thinning strategies

This simulation focuses on the growth response of Douglas-fir monocultures, again represented by artificially generated stands, to different alternatives of thinning. The four assumed thinning regimes called *questionnaire, traditional, new* and *control* differ according to schedule, frequency, and intensity and are explained in detail in paper 2). The simulation results are shown in Figure 14 that suggests: Few intensive thinning entries, represented by variant *new*, are most productive in terms of the final stem volume (left). But when including all components that provide available timber (remaining plus removed), all variants lead to similar results.

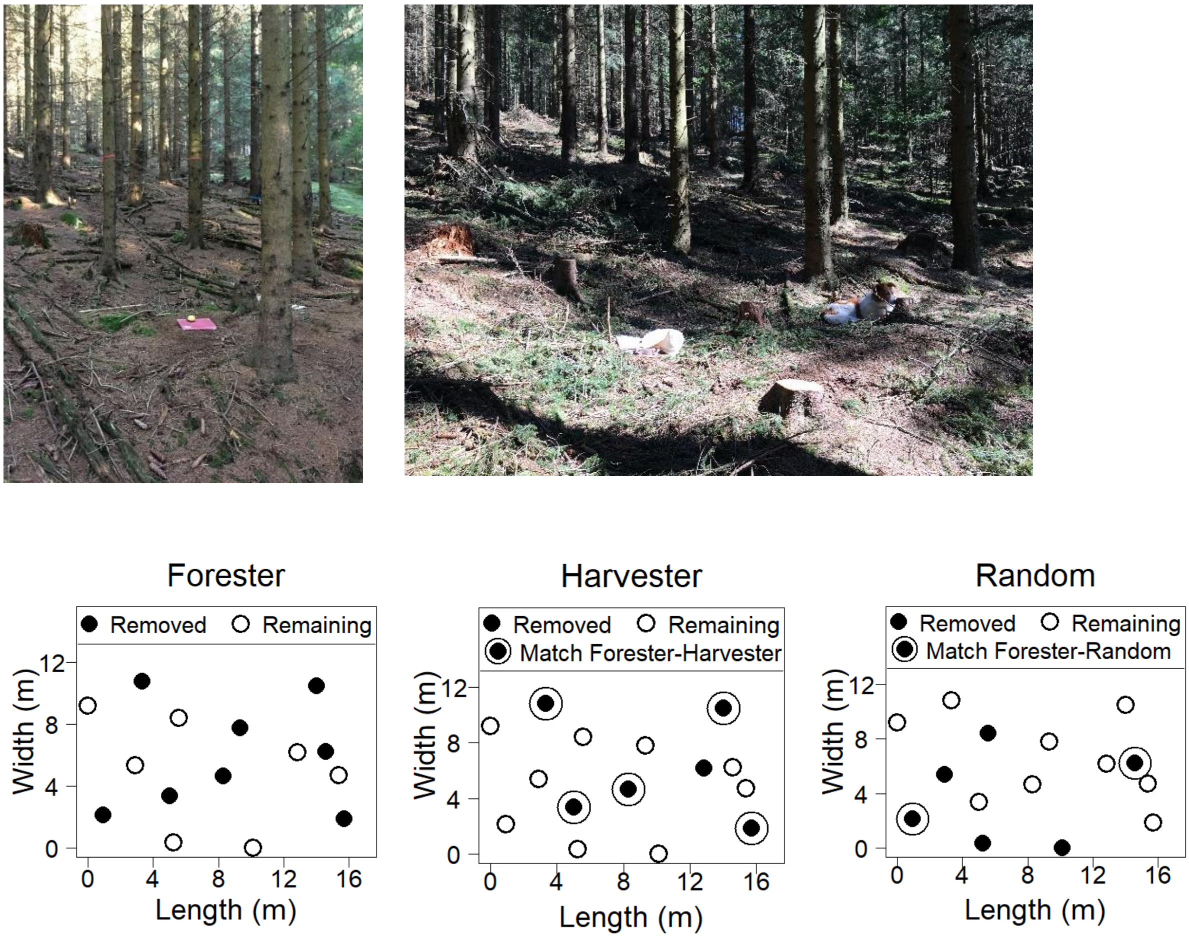
Figure 14 Left hand: Development of a pure Douglas-fir stand after three different thinning variants called questionnaire (many moderate entries), traditional (three medium interventions), and new (two early and intensive removals), with stem volume development vs. age (the results represent the mean of 10 simulation-runs with grey band delineating the confidence interval at α = 0.05). Variant New yields the highest remaining volume. Right hand: In terms of total available stem wood (remaining plus removed volume), all three variants are balanced.



3.5 Growth after tree marking and after selection by harvester operator

The core interest of this study (for more details see paper 3) consists in the question if there are differences i) in the characteristics of trees after removal, and ii) the development of the stands after removal, when comparing three thinning variants, forest manager, harvester operator, and the random thinning algorithm of the simulator. An essential prerequisite of this study was that the harvester operators, first were highly experienced, and second had executed the tree marking as indicated by the forest managers, for many years. Figure 15 illustrates a stand after the tree marking by a forest manager, with the attached ribbons (top left), and after the selection by a harvester operator with an included removal by harvester machinery. The bottom section of the figure provides a schematic overview on the stand after all three assessed thinning variants, forest manager, harvester operator, random.

Figure 15 Example of a stand (same stand and same perspective) after tree marking by forest manager (top left) and after the harvester selection with included physical removal of the trees (top right). On the section below all three possible thinning outcomes are represented, forest manager (bottom left), harvester operator (bottom middle), random (bottom right). Compared with the eight trees removed by the forest manager (bottom left), the harvester operator removes five identical trees (62%, bottom middle). The match of the random intervention with the forest manager´s selection amounts to two trees (bottom right).



The study reveals a conformity between forest manager and harvester operator (match of removed trees of about 70%). This also applies when focusing on the characteristics of removed trees such as the social class according to Kraft (1884) and the dbh-class. Table 10 displays that in three out of four Pearson´s Chi-squared tests (social class in first and second thinning, dbh-class in second thinning) no differences between forest manager and harvester driver are given. But when including the random procedure in the comparison, in all cases differences are detectable.

Table 10 Mean total number of trees before thinning (N/ha - see first line) and the number of removed trees per hectare by selection method (FORESTER, HARVESTER, RANDOM). The statistical evaluation was realized on the basis of the real removals, while the table shows the values per ha.

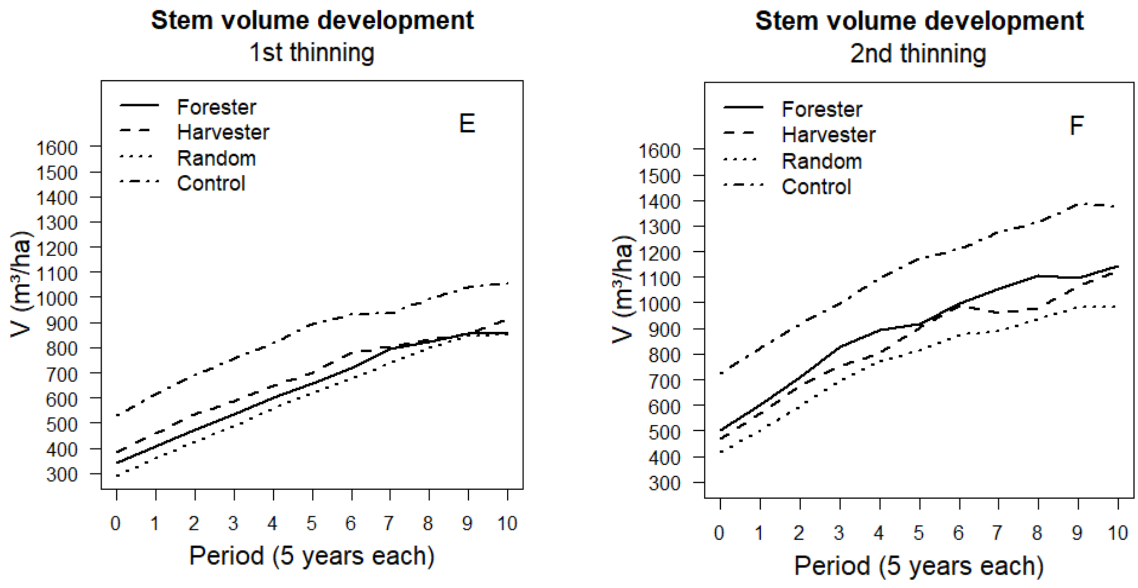
Treatment	Method	Social class						dbh class (cm)						
		1	**2**	**3**	**4**	**5**	**Σ**	**1–10**	**11–20**	**21–30**	**31–40**	**41–50**	**51-60**	**Σ**
1st thinning	*N/ha*	216	499	490	247	211	1663	144	912	526	72	9	0	1663
	Forester (F_N/ha)	24	147	272	193	60	696	19	405	253	19	0	0	696
	Harvester (H_N/ha)	27	118	234	202	118	699	81	433	175	11	0	0	699
	Random (R_N/ha)	98	190	201	123	95	706	50	388	206	61	0	0	706
2nd thinning	*N/ha*	189	378	189	132	63	951	6	113	485	309	31	6	951
	Forester (F_N/ha)	19	125	112	112	62	430	6	106	256	62	0	0	430
	Harvester (H_N/ha)	38	133	139	70	57	437	6	114	222	89	6	0	437
	Random (R_N/ha)	74	178	74	67	18	411	0	43	215	129	25	0	411
Pearson´s Chi-squared Test														
		df	χ^2		$\chi^2_{5\%}$		*P*	*df*	χ^2		$\chi^2_{5\%}$		*P*	
1st thinning	$F_N/ha - H_N/ha$	4	5.04		9.5		0.28	3	10.7		7.8		0.01*	
	$F_N/ha - H_N/ha - R_N/ha$	8	27.6		15.5		0.01*	6	20.2		12.6		0.01*	
			.7											
2nd thinning	$F_N/ha - H_N/ha$	4	3.17		9.5		0.53	4	2.17		9.5		0.70	
	$F_N/ha - H_N/ha - R_N/ha$	8	17.4		15.5		0.03*	8	16.4		15.5		0.03*	

*Significantly different at α = 0.05

A similar finding results when taking in account the damages on remaining trees after thinning by three variants. For both assessed categories stripping damages as well as all other damages/defects (red rot, broken top, doubled tree-top) no significant difference between forester and harvester driver are detectable.

And finally, the resulting growth after a 50-years simulation shows no significant differences between the thinning interventions by forest manager, harvester operator, and random (assessed by ANOVA and corresponding Tukey Test). In contrast, when comparing the variants that include thinning with the no-thinning/control alternative, a highly significant difference is given. Figure 16 shows the results of this simulation, according to first (left) and second thinning (right). Again, it becomes clear that in terms of thinning, a conformity between forest manager and harvester driver is given.

Figure 16 Standing timber volume development per hectare (V/ha) for 50 years of growth after treatment according to the tree selection method FORESTER, HARVESTER, RANDOM and no thinning (CONTROL).



4 Discussion and conclusion

Research on Douglas-fir in the European context is mainly concerned with questions addressing provenance and genetics, ecological aspects including a potential invasiveness of the tree species, and wood quality issues, while analyses on the management are underrepresented.

It was the aim of the present thesis to contribute to a better understanding of how to manage Douglas-fir stands in central Europe properly, by applying the simulation approach. As a preparative step, the growth simulator MOSES was calibrated for Douglas-fir, and second, the currently practiced Douglas-fir management guidelines were assessed, based on a survey extending on central Europe. Two main topics with a need for clarification were identified: stand establishment and thinning.

On that basis, two categories of research interests were defined i) practices around stand establishment including the development of Douglas-fir natural regeneration, the planting layout in combination with common beech and Norway spruce, the development of Douglas-fir plantations on limestone (paper 1, paper 2), and ii) thinning issues aiming at beneficial thinning guidelines (paper 2) as well as a practical facilitation of the thinning operation (paper 3).

When managing forests, it is a crucial issue to regenerate the stands in a proper way. The natural regeneration of stands nowadays is a widespread principle since it corresponds to a fundamental self-definition of modern forestry. Such has been formulated by (Spiecker, 2003), who differentiated three stages in the European forestry history, exploitation, restoration, and conversion as the dominating doctrine at present. The latter concept includes, among others, the idea of re-establishing stands by the vegetation that emerges spontaneously on a particular site, in order to generate environmentally well adapted, vital and robust stands.

One essential interest when simulating the development of Douglas-fir natural regeneration was to clarify the performance of the young trees in mixture with beech and Norway spruce, the main competitors in context of the established field trials. The results suggest that Douglas-fir does re-colonize sites after opening-up the canopy cover, but immediately after gets under competitive pressure coming from beech (Figure 9, left, Figure 12, left). Consequently, at this development stage, a support of Douglas-fir by appropriate management measures is highly required (Figure 12, bottom right). Likewise, it should be avoided to expose young Douglas-fir to inter-specific competition when establishing mixed plantations. Such avoidance can successfully be achieved by arrangements in monospecific patches, where the single tree species grow in separation from each other, as demonstrated by respective simulations (Figure 13).

The listed insights are corroborated by literature. A satisfying natural regeneration potential of Douglas-fir is reported by (Angelier, 2007; Angelier et al., 2004). The fundamental role of the early stage for the generation of strong roots and crowns as an essential requirement for the later growth, has been outlined by (Spiecker et al., 2019). Growth deficiencies at the immediate post-regeneration stage, primarily due to competitive pressure, are observed by (Knoerzer, 1999; Kownatzki et al., 2011). (Curtis et al., 1998) outline the need of supportive measures in order to counteract such difficulties. Based on planting trials in Germany, (Kownatzki et al., 2011) show that the survival of Douglas-fir is clearly enhanced by the growth inside homogeneous patches, remote from the competitive species.

When the discussion comes to the establishment of Douglas-fir plantations on limestone, the popular opinion of many foresters (perceptible also in the context of this study) is of that kind that the young trees have difficulties soon after planting. Yet, research on that topic is limited and available findings are rather inconsistent. According to (Aas, 2008) Douglas-fir should be planted on acidic soils with pH values between 5 and 6, while studies from (Vor et al., 2015) suggest that Douglas-fir shows ubiquitous and soil vague characteristics. However, there is agreement among the authors that freely available carbonate in the topsoil is detrimental and might lead to the formation of chloroses (e.g. Otto et al., 2020). Thus, it was one main purpose of the here conducted experiment to contribute to a respective clarification (Ammerer et al., 2021). Since the experiment is still in the initial phase, the presented results are considered preliminary. However, the analyses on mortality indicate that no remarkable drop out occurred within the first years after plantation (Figure 10, left) when compared with information collected by the survey (Table 5). The finding that vital trees contain less nutrients than weak trees (Table 4) is surprising and should be further investigated. Calcium and magnesium seem to be of relevance for the vitality of the young trees, as suggested by the *RandomForest* analysis (Figure 11). Such substances are essential for soil conditions as present on the assessed experimental sites, since *Ca* is constitutive for the formation of calcium carbonate ($CaCO_3$), and *Mg* is the differential element between limestone and dolomite ($CaMg(CO_3)_2$) (Table 3). When considering that the poorly developed trees of provenance NW-Deutschland for both substances *Ca* as well as *Mg* show higher amounts than provenance Ashford (Table 4), and further that the mortality rates of NW-Deutschland are significantly higher than Ashford (Figure 10), we might indirectly conclude that an increase of *Ca* as well as *Mg* affects negatively the vigour of young Douglas-fir trees on limestone, in the context of our experiment. A study from (Bergante et al., 2020), conducted in the context of poplar plantations in the Po plain in northern Italy, shows that out of four tested treatment alternatives i) irrigation ii) irrigation + fertilization iii) fertilization iv) no treatment, only irrigation exerts a significant impact on the growth of the poplars. Moreover, it suggests that the sole water donation (variant i) is superior to all variants where fertilization is added (variant ii, variant iii). One of the explanations provided by the authors suggests that the uptake and decomposition of nutrients consumes water. This way it subtracts water, which far is the most relevant growth resource in the environment under consideration, to other physiological processes.

The simulations on beneficial thinning guidelines (paper 2) revealed Douglas-fir as flexible towards the silvicultural repertoire, since several thinning strategies lead to a satisfying result, such as i) late, often and moderate ii) early, rarely and intensive and iii) medium in schedule, frequency and intensity (Figure 14). Hence, at this stage Douglas-fir is rather easily treatable and so to say compensates for the demanding nature in childhood and youth. This finding likewise is confirmed by operation and research. That a variant with late, rare, and light entries like the here tested variant *Questionnaire* (Figure 14) is a reasonable option, reflects from the fact that it is being applied by many of the companies contributing to the survey (Table 5). The opposite variant (early, few, and heavy entries) also has been proven as a reasonable alternative, e.g. (Bailly and Dechamps, 1997) describe the successful use of a thinning procedure similar to variant *New* (Figure 11) for the Massif central/Auvergne in France.

The case study on tree marking (paper 3) investigates a very practical issue in the context of thinning. In central Europe, the marking of trees previous to removal is a traditional element in the operational repertoire of forest managers and is considered advantageous for a satisfying development of forest stands (Dengler, 1935; Frank, 2008; Neumann, 2003; Schädelin, 1942). However, it consumes resources in the form of time and money (Cimon-Morin et al., 2010; Kellogg et al., 1998; Sydor et al., 2004), so that in many cases it might be seen as a reason why thinning is being skipped by the forest owners. The research on this issue that is available so far, concentrates on the impact of tree marking on the productivity of the harvester machine (Bergström et al., 2010, 2007; Cosby et al., 1984; Holzleitner et al., 2019), suggesting that there is such impact, but regardless whether executed by forest manager or harvester machine operator. Spinelli et al. (2016) investigated the effect of thinning as performed by several professional groups on the tree selection, again resulting in no emerging differences. Lexer (1993) compared tree marking by forest manager versus tree selection by harvester operator within broadleaf stands, with the result that likewise no differences in the characteristics of the selected trees are detectable.

In contrast, the peculiarity of the present study (paper 3) consisted in the idea of simulating the further development of stands after the different selection variants. The results show no difference neither in tree characteristics (removed trees), nor in quality criteria (remaining trees) after removal by forest manager or harvester operator (Table 10, Figure 16). Even after a simulation period of 50 years, no relevant differences between the two approaches appear, e.g. in terms of final stem volume or mean diameter. However, a clear difference can be detected between variants with and without thinning (Figure 16).

The thinning experiment was done in Norway spruce stands since Douglas-fir for that purpose was not available. Basically, the very fundamental interest was to find out whether the two mentioned protagonists, forest manager and harvester operator, select different trees for removal or not. It is important to stress that the thinning instructions for both, forest manager as well as harvester driver, were identical, so that for the first part of the experiment, the tree selection, by nature similar outcomes could be expected. However, for the second part, the simulation of the growth after thinning, indeed it would have been relevant if differences had been detected. Since different tree species react diversely to unequally available resources, in that case the simulation could not have been accomplished reasonably. This applies especially to different strategic types (Grime, 2006) as represented by Douglas-fir and Norway spruce. Douglas-fir as a seral species displays the characteristics of a pioneer much more than Norway spruce as a climax strategist. Young Douglas- fir trees demand more light than the equivalents from spruce, so that under different conditions after thinning the growth probably would be different. Since no significant differences appeared (Table 10), but even more a high percentage (about 70%) of the trees were identically selected by forest manager and harvester operator, we confidently proceeded to the core element of the investigation, the simulation of the growth after thinning. Nevertheless, it is admitted that this aspect is relevant for future investigation, and the experiment should be repeated and ascertained in Douglas-fir stands.

All the discussed growth characteristics of Douglas-fir, the proliferous natural regeneration at times, the preference for dissociated (separated from other species) growth, the sensitivity to competing tree species, the flexibility in the thinning stage, can be traced back to the natural growth of Douglas-fir stands in the native range. In natural stands in the Pacific Northwest (PNW), Douglas-fir principally gets displaced by more shade tolerant species (Franklin et al., 2002), especially Western hemlock (*Tsuga heterophylla*), Western red-cedar (*Thuja plicata*), red alder (*Alnus rubra*), and the so-called true firs such as noble fir (*Abies nobilis*), silver fir (*Abies amabilis*), alpine fir (*Abies lasiocarpa*) and grand fir (*Abies grandis*). Under such circumstances, the Douglas-fir rejuvenation naturally is promoted by the fire ecology (Agee, 1996) that creates optimal growth conditions (Hermann and Lavender, 1990) in terms of i) wide open areas providing sufficient light ii) the bare mineral soil as being advantageous for Douglas fir but less advantageous for the competitors iii) the seed abundance and iv) the shelter under the canopy of mature trees, altogether corresponding to the before-listed tree species characteristics. In addition, natural Douglas-fir stands in the final development stage dispose of rather few exemplars, which is reasoned by a density-dependent high mortality rate (DeBell and Franklin, 1987; Franklin et al., 2002) that spontaneously reduces the stem number.

Also the human treatment of Douglas-fir stands in the PNW is quite mindful of the mentioned growth characteristics. When rejuvenating old growth stands, respective management guidelines aim at reproducing the above-described growth conditions after forest fire as best as possible by adopting the shelterwood system (Hermann and Lavender, 1990; Williamson, 1973). When managing artificial stands, rejuvenation is done by large clear cuts (Agee, 1996; Curtis et al., 1998). In this case, intensive early operations for the re-establishment, such as mechanical site preparation (e.g. soil scarification), slash removal, and longstanding and intensive control of competing vegetation, are indispensable (Curtis et al., 1998). Moreover, the majority of Douglas-fir plantations in the PNW are monocultures (Briggs, 2007; Talbert and Marshall, 2005). Thinning measures basically are not being considered an essential management requirement. Due to the self-thinning capacities of the tree species, removals often are not carried out as thinning measures in the proper sense, but as a way of capturing mortality (Talbert and Marshall, 2005; Worthington and Staebler, 1961). Indeed, according to (Curtis et al., 1998), the concept of commercial thinning originates from Europe and was applied there long time before coming to the Pacific Northwest.

It reflects from the development of natural Douglas-fir stands (fire ecology, self-thinning, rapid height growth) as well as from the management principles in the PNW (shelterwood treatment, effortful investment in early operations, prudent thinning) that Douglas-fir is a demanding tree species at early stage, but later-on shows a development that autonomously matches with management goals.

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6 List of Figures

7 Appendix

Paper 1 Eberhard, B., & Hasenauer, H. (2018). Modeling Regeneration of Douglas fir forests in Central Europe. Austrian Journal of Forest Science, 135(1).

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Modeling Regeneration of Douglas fir forests in Central Europe

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Keywords: Douglas fir, Pseudotsuga menziesii, natural regeneration modeling, invasiveness, tree growth modeling

Abstract

Modeling regeneration and growth of juvenile trees is highly relevant for simulating the growth behaviour of forest stands, which permits evaluating forest management options for climate change adaption. An important adaptation option is tree species selection. Douglas fir, a non-native tree species from north western America, was introduced in many Central-European countries and is now one of the most frequent non-native tree species in Europe. In this study, we develop a regeneration tool to predict the regeneration establishment and juvenile tree height growth of Douglas fir in central Europe. We implement this regeneration tool in the tree growth simulator MOSES and test the potential invasiveness using data from 28 Douglas fir dominated stands with natural regeneration located in Austria and southern Germany. Our results suggest that regeneration establishment and juvenile tree growth is driven by overstory competition as well as edge effected incidence of light. Douglas fir re-

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generation shows no invasive behaviour, but in contrast requires forest management to survive.

1. Introduction

Douglas fir (*Pseudotsuga menziesii (Mirb.)*) is an important non-native tree species in Europe and has become of increasing interest as an adaptation option to climate change. It is also considered as a potential alternative to Norway spruce (*Picea abies L. Karst*) for low elevations (Lavender and Hermann, 2014) because of its enhanced drought resistance and excellent growth behaviour (Eilmann and Rigling, 2012; Pharis and Ferrell, 1966).

Within its native distribution range in western North America, two distinct varieties of Douglas fir are known: (i) the coastal variety (*P. menziesii* var. *menziesii*) and the (ii) interior variety (*P. menziesii* var. *glauca*). The coastal variety grows along the coast and the west phasing slopes of the Rocky Mountain range from British Columbia, Canada to California, USA. The interior variety (also called Rocky-Mountain variety) grows further east from British Columbia across the Rocky Mountains to New Mexico (USA) (Eckenwalder, 2009).

The distribution of Douglas fir fir in Europe is the result of a long introduction history, which started in 1826 (Köble and Seufert, 2001). In Austria the share of Douglas fir on the total growing stock is about 0.2%, and covers about 10.000 ha (ÖWI, 2016). The Douglas fir forests are located mainly in the Eastern part of Austria. According to the Austrian National Forest Inventory, the area of Douglas fir has doubled since 2002 (Gabler and Schadauer, 2008). In Germany 2% of the growing stock are Doulas fir and the spieces covers about 218.000 ha (BMEL, 2014).

While for the Douglas fir plantations established after the 1960 the seed origin is known, the old Douglas stands established prior to the 1960, are of unknown origin. These stands have existed longer than one rotation cycle and produce abundant natural regeneration, which could be referred to as the „second generation". Hintsteiner et al. (2018) showed, that most of these old Douglas fir stands originate from the recommended areas in North America (mainly from the provenances Ashford Elbe and Snoqualmie River, which are located in the North Cascades from the US state of Washington, in the north of the river Columbia).

Successful forest management requires information about the regeneration dynamics of forests and how this may be implemented in existing growth models. In principle two types of growth models are in place: (1) yield tables, which assess the mean stand development and (2) tree growth models which predict the individual tree growth according to age, competition and site conditions. A typical example is tree growth model MOSES – Modeling stand response (Hasenauer, 2006; Klopf, 2014; Thurnher et al., 2017). MOSES is parametrized for several important European tree species including Douglas fir (Mayer, 2014), but lacks a regeneration tool for Douglas fir.

Regeneration predictions are commonly based on (1) the establishment of regeneration and (2) the juvenile growth and tree mortality (Biber and Herling, 2002; Golser and Hasenauer, 1997; Hasenauer and Kindermann, 2006; Hynynen et al., 2002; Schweiger and Sterba, 1997) . A regeneration model consists of several equations which predict the number of juveniles by species, the survival, and height growth of new established trees. Note that although damage to seedling establishment and regeneration growth due to browsing, timber harvesting, etc. should be taken into account, relatively little information is available for Douglas fir.

Forest regeneration tends to be sporadic, i.e. little or no regeneration for some years and large amounts in those years when it does occur. Thus a two-stage approach of regeneration modeling is commonly applied (Ferguson et al., 1986; Ferguson and Carlson, 1993; Miina and Saksa, 2006; Schweiger and Sterba, 1997; Solomon and Leak, 2002), where first, the probability of regeneration on a given plot is predicted and then the juvenile tree growth is predicted.

The objectives of this study are (1) to apply the regeneration approach suggested by Hasenauer (1994) for Douglas fir forests in central Europe, (2) to evaluate the model results and (3) to implement them into the tree growth model MOSES and analyse the invasiveness of Douglas fir.

2. Methods

The estimation of the probability of regeneration follows the approach suggested by (Kindermann, 2004), (Hasenauer and Kindermann, 2006) and is a generalized linear model (GLM):

$$p = \frac{1}{1 + e^{-a \cdot x}} \qquad (1)$$

Where p is the probability of regeneration, a, are the coefficient estimates of the vector x covering the independent variables *konk*, a measure for competition, dbh_{max}, the maximum diameter at breast height by tree species in the overstory of a sample plot, and *Hum* the humus type. The competition index *konk* includes both the competition in overstory as well as within regeneration layer:

$$konk = \frac{\sum((a * mdbh)^b \bullet n_{rep} \bullet c)}{10000} \qquad (2)$$

n_{rep} is the number of stems per ha represented by each tree within a sample plot. For example, the blow-up factor for a fixed sample area of 16 m^2 is 625 (10.000/16=625). *mdbh* is a proxy for the crown area of a tree. For trees ≤ 1.3 m in height the *mdbh* is set to the height of the tree in meters and for taller trees *mdbh* is calculated by its dbh in cm plus 1.3. *a, b, c* are species specific coefficients according to Kindermann (2004) and are calculated iteratively until the plots with and without regeneration can be differentiated. Coefficients *a, b, c* for Norway spruce and Common beech have been taken from Kindermann (2004).

The *density regeneration* approach by tree species (N_{BA}) is equal to the regeneration model (see equation 1) and incorporates the same independent variables, *konk*, dbh_{max} and *Hum*. The only difference is that a Poisson algorithm is used for estimating the coefficients:

$$N_{BA} = e^{a \bullet x} \qquad (3)$$

With a the coefficient estimates of the vector x, which consists of the variables konk, dbhmax,, Hum. Equation (3) is only applied if regeneration establishment is predicted.

Predictions of the height growth of juvenile trees are based on the potential modifier approach (see Golser and Hasenauer 1997), where in a first step (i) the 5-year height increment potential of a given tree is derived from site index functions. In a second step (ii) this potential height increment is reduced to actual height growth applying two reduction factors, Overstory competition expressed as the *CCF*, and the competition within the regeneration itself, which is derived as the sum of the trees taller than the subject tree. The compensation factor *SUMD* addresses potential compensation effects in height growth due to the edge effected incidence of light. The equation has the following form (Golser and Hasenauer 1997):

$$ih = ih_{pot} \bullet \left(1 - e^{\frac{-1}{a \bullet CCF + b \bullet nTaller} + c \bullet SUMD}\right) \qquad (4)$$

Where *ih* is the 5-year height increment, ih_{pot} is the potential 5-year height increment derived from site index functions, *CCF* the Crown Competition Factor according to Krajicek et al. (1961), N_{Taller} the number of trees taller than the subject tree, and *SUMD* the compensation factor of edge effected incidence of light.

The calculation of ih_{pot} (the potential 5 year height increment) requires the selection of a site index (*SI*) function. We used the height curve from Mitscherlich/Richards (see Kindermann and Hasenauer, 2005; Thurnher et al., 2017), which determines the top height of a tree according to stand age, site index and species specific coefficients. These coefficients have been taken from Kindermann and Hasenauer (2005), who calibrated the height curve for all main tree species in central Europe, including Douglas fir. Since we wanted to employ the dominant height development of Douglas fir with data from Eckmüllner (2015), we re-calibrated the function. The dominant tree height needed for the definition of site index (SI) was derived according to Pollanschütz (1975). Missing tree heights of the sampling data were derived according to Peterson (1985).

The crown competition factor *CCF* was calculated according to Krajicek et al. (1961) with coefficients for open grown trees from Hasenauer (1997).

SUMD, the incidence of light, is a compensation factor for the two described competition measures *CCF* and N_{Taller}, and is quantified by the weighted sum of distances (*SUM of Distances*) according to Golser and Hasenauer (1997):

$$SUMD = \left(\sum_{n=1}^{N_d} \frac{1}{DIST_i} \bullet \frac{2DH}{N_d}\right) - 1 \qquad (5)$$

Where N_d is the number of directions, *DIST* the distance to the stand edge, and *DH* the dominant height of the stand.

3. Data

We obtained 28 Douglas fir stands with natural regeneration growing in Austria and Germany. The plots with a minimum area of 0.25 ha cover a wide range of bioclimatic regions (latitude between 47.5° N and 49.0° N, longitude between 8.6° E and 16.4° E). The share in the basal area of Douglas fir had to be > 75% to be selected. The data collection followed a hierarchical structure including three layers, (1) the overstory with trees > 10 cm in *dbh*, (2) an intermediate layer covering trees > 1.3 m in *h* but ≤ 10 cm in *dbh*, and (3) the regeneration layer (h ≤ 1.3 m).

Overstory data were collected at a fixed sample plot with a radius of 20 m. Trees species, dbh, horizontal distance to the plot centre, and azimuth was recorded. Tree height and heights to life crown was recorded. The same information was collected on four subplots representing the intermediate layer. Stand age was determined from increment cores. The summary statistics of the overstory data are given in Table 1.

Table 1: Summary statistics of the 28 Douglas fir stands. Elev is elevation, Temp is mean annual temperature, Precip is mean annual precipitation, N/ha is stem number per ha, BA is basal area, V is stem volume, DH is dominant height, CCF is Crown Competition Factor, SI is site index as dominant height at age 100.

	Site-characteristics			**Stand-characteristics**						
Plot Nr.	Elev (m)	Temp (°C)	Precip (mm)	Age	N/ha	BA/ha (m²)	V/ha (m³)	DH (m)	*CCF* (%)	*SI*
1	290	9.9	600	90	136	24	324	35	135	35
2	460	9.6	720	84	164	42	720	43	308	46
3	560	9.1	790	82	211	43	721	43	368	47
4	520	9.3	770	40	399	28	278	22	360	42
5	360	9.5	650	38	558	36	371	25	573	49
6	370	9.1	570	52	188	20	223	27	142	40
7	400	9	580	108	61	17	219	33	77	30
8	430	9.1	640	58	748	61	822	33	906	47
9	440	8.9	620	43	306	35	474	31	413	57
10	410	9	610	42	285	32	386	29	237	53
11	330	9.4	960	70	165	41	595	39	340	47
12	530	7.9	710	121	247	55	863	40	568	36
13	820	7.1	2100	110	160	65	1317	54	407	50
14	640	8	900	109	76	38	740	51	279	48
15	660	7.9	910	105	108	41	829	54	378	50
16	590	8.3	890	104	207	42	821	51	263	48
17	660	8.1	1110	54	324	52	650	33	483	49
18	810	7.7	1450	95	221	53	821	43	659	43
19	480	8.8	960	100	226	65	1199	49	535	47
20	680	7.3	900	72	360	45	695	37	352	44
21	480	8.6	780	58	221	42	636	37	448	54
22	670	8.2	1120	62	350	48	726	39	571	52
23	660	7.9	870	109	146	59	1080	54	415	47
24	700	7.7	900	40	544	27	245	22	215	40
25	700	7.8	890	41	612	39	391	23	444	42
26	890	7	1050	60	298	46	673	37	412	50
27	450	9.1	970	51	366	36	453	34	559	57
28	520	8.8	1010	50	279	44	579	32	334	51

On each Douglas fir stand four regeneration subplots covering a size of 2 x 2 m were established in four directions 10 m from the plot centre (Golser and Hasenauer (1997). On these subplots representative trees by height class and species group were selected to record the tree height and 5-year height increment. Three species-groups (Douglas fir, Other conifers, Other broadleaves) and 4 height classes (1 cm-20 cm; 21 cm-50 cm; 51 cm-100 cm; 101 cm-130 cm) were defined. The group "Other conifers" include mainly Norway spruce, and "Other broadleaves" mainly Common beech. For recording trees in the intermediate layer (ranging from h > 1.3 m to dbh ≤ 10 cm), the size of the four subplots was enlarged to 5 m by 5 m. Again the species group, *dbh*, tree height and height to the life crown base was recorded. More details on the recording of regeneration data can be found in Golser and Hasenauer (1997).

Potential compensatory effects on juvenile tree growth due to edge effected incidence of light (see Golser and Hasenauer 1997) were addressed by measuring the distance in 8 directions from the four subplot centres to the stand edge if the distance was less than twice the dominant tree height e. g. about 60 m. The humus type was classified according to three categories: mull, mull-behaved decay, decay. A summary of the available data for calibrating regeneration establishment and juvenile tree height growth is shown in Table 2 and Table 3.

Table 2: Summary of the regeneration data, where D is Douglas fir, Co Other conifers, Br Other broadleaves, Re is regeneration (≤ 1.3 m in height), IL is the intermediate layer (> 1.3 m in height and ≤ 10 cm in dbh), dbh_{max} *is maximum diameter, konk the competition index according to equation (2), Hum is the humus type, Mull is mull, Mod is decay, MuMo is mull-like decay. "-" indicates that no adult tree was on the plot.*

Plot Nr.	N_{Re_D} (N/ha)	N_{IL_D} (N/ha)	dbh_{max_D} (cm)	N_{Re_Co} (N/ha)	N_{IL_Co} (N/ha)	dbh_{max_Co} (cm)	N_{Re_Br} (N/ha)	N_{IL_Br} (N/ha)	dbh_{max_Br} (cm)	*konk*	*Hum*
1	0	0	68	0	0	59	0	0	-	1.5	Mull
2	0	0	69	0	0	-	10625	900	-	3.8	Mull
3	0	0	66	0	0	-	0	200	-	3.7	Mull
4	0	0	29	0	0	44	0	0	-	4.4	Mod
5	0	0	50	0	0	-	24375	0	23	4.6	Mod
6	59357	0	43	0	0	-	4375	0	-	1.9	Mull
7	1250	300	80	0	0	-	0	0	-	1.5	Mull
8	43125	0	52	1250	0	31	0	0	21	6.3	MuMo
9	0	0	43	0	0	-	0	0	-	3.8	Mod
10	6250	0	46	25000	0	-	625	0	-	2.6	MuMo
11	6875	100	73	17500	0	23	30625	500	-	5.5	Mull
12	5000	100	77	6250	300	-	1875	100	-	5.5	Mod
13	0	0	125	0	0	-	0	0	-	3.4	Mull
14	3750	0	96	0	200	64	0	700	-	3.1	Mull
15	1250	500	95	16250	1400	-	0	100	-	5.8	Mod
16	1250	200	99	8125	200	-	625	200	-	3.1	Mod
17	0	0	57	0	0	40	0	0	-	5.3	Mod
18	1875	100	91	11250	2200	-	18750	2800	44	7.5	Mull
19	0	0	91	625	100	-	0	0	-	4.4	Mull
20	37500	0	71	103125	0	-	625	0	-	6.3	MuMo
21	625	0	70	1250	0	44	31250	0	33	3.5	Mod
22	0	0	70	71250	600	59	625	1600	-	10.2	Mod
23	0	0	97	0	0	77	0	100	40	2.4	Mull
24	0	0	43	0	0	-	0	0	-	3.1	Mull
25	0	0	40	0	0	-	0	0	-	4.8	Mull
26	0	0	69	0	0	39	0	1000	-	4.3	Mull
27	0	0	54	0	200	-	3750	5700	23	4.9	Mull
28	0	0	55	0	0	-	625	700	-	3.4	Mull

Table 3: Summary of species-specific data for calibrating the 5-year juvenile tree growth.

	Douglas fir				Other conifers				Other broadleaves			
N	39				57				44			
Variable	**Min**	**Mean**	**Max**	**Sd**	**Min**	**Mean**	**Max**	**Sd**	**Min**	**Mean**	**Max**	**Sd**
h_{Rep}	3.5	30.1	125.0	33.9	3.5	40.4	120	32.6	6.0	49.1	127	34.4
ih_{obs}	6.5	25.7	66.0	14.3	2.5	21.9	56.0	12.4	7	33.4	105	21.6
ih_{pot}	134	238	295	29.5	216	271	338	30.2	89.7	138	237	47.8
N_{taller}/m^2	0	0.79	4.0	1.06	0	1.26	4.0	1.24	0	0.64	3	0.84
CCF	77.1	395	906	205	237	457	906	157	142	433	659	144
SUMD	0	1.03	5.94	1.32	0	0.71	3.83	1.02	0	0.69	3.83	0.91

N	Number of representative trees
h_{Rep} [cm]	Height of the representative tree
ih_{obs} [cm]	Observed 5-year height increment of the representative tree
ih_{pot} [cm]	Potential 5-year height increment according to SI-curves
N_{taller}/m^2	Number of trees per m² taller than the subject tree
CCF	Overstorey crown competition factor (trees > 10cm dbh)
SUMD	Weighted sum of distances / light-incidence due to edge effect
Sd	Standard deviation

4. Analysis and results

4.1 Regeneration model for Douglas fir

4.1.1 Regeneration establishment

We start the calibration by assessing the probability of Douglas fir regeneration establishment (P_{BA}) with a logistic regression:

$$p_{BA} = \frac{1}{1 + e^{-1 \cdot (a * konk + b \cdot dbh_{max} + c_{Hum})}} \qquad (6)$$

Note that P_{BA} is a binary coded (yes/no) variable. Thus ML (Maximum Likely Hood) procedure is required for deriving the coefficient estimates (Hasenauer and Kindermann, 2006; Monserud and Sterba, 1999; Pretzsch et al., 2002). The estimated coefficients are given in Table 4. Since we cannot assume that on each plot all the established regeneration survives, we compare the results from equation (6) with a random number ranging between 0 and 1. If the random number is higher than the calculated probability, a successful regeneration establishment is assumed otherwise P_{BA} is set equal to zero.

4.1.2 Regeneration Density

Once it is decided that regeneration occurs, we can estimate the number of trees by tree species and per m² (N_{BA}) according to equation (7):

$$N_{BA} = e^{(a \cdot konk + b \cdot dbh_{max} + ci_{Hum})} \qquad (7)$$

konk is the competition index according to equation (2) dbh_{max} the maximum diameter at breast height for a given tree species, and *Hum* the humus type, *a, b, c* are the corresponding parameter estimates. Parameter *c* has three manifestations, mull, mull-behaved decay, decay. Parameters for Douglas fir are represented in Table 4.

Table 4: Variables and coefficient estimates for the models of probability and density of regeneration of Douglas fir

Variable	coeff	P Dou	N Dou
konk	a	-0.1825^{x}	0.1288^{x}
$dbh_{max,Dou}$	b	-0.0331^{x}	-0.0288^{x}
Mull	c_1	n.c.	n.c.
MuMo	c_2	n.c.	n.c.
Mod	c_3	n.c.	n.c.
n		28	28
NULL dev		38.8	52.0
Res dev		28.1	32.0

significant with *** α = 0.001 ** α = 0.01 * α = 0.05 ▪ α = 0.1

konk	Measure of concurrence
Mull, Mod, MuMo	Mull is mull, Mod is decay, MuMo is mull-like decay
coeff	coefficient
n	Number of stands
NULL dev	NULL deviance
Res dev	Residual deviance
P Dou	Regeneration probability of Douglas fir
N Dou	Regeneration density of Douglas fir
x	Not certain at α = 0.05 and used for the regeneration model.
n.c.	Not certain at α = 0.05 and not used for the regeneration model.

4.1.3 Juvenile tree growth

Next we derived coefficients for calculating juvenile tree height growth according to equation (4). We also do this for the species groups „Other coniferous" and „Other broadleaves" so that we can compare the juvenile tree height growth of Douglas fir with the other species groups on our forest plots. The estimated coefficients follow a non-linear regression using the statistical software R (Team, 2014). The results are given in Table 5.

Table 5: Variables and coefficient estimates for the tree juvenile height increment model.

Variable	Coeff	Douglas fir	Other conifers	Other broadleaves
CCF	a	0.05481***	0.02831***	0.01474**
N_{Taller}	b	0.12137	1.36709	0.97403
SUMD	c	-0.04093***	-0.00556	-0.02883
n		39	57	44
Se		0.167	0.128	0.235

significant with *** $\alpha = 0.001$ ** $\alpha = 0.01$ * $\alpha = 0.05$
CCF Crown Competition Factor
N_{Taller} Number of trees taller than the subject tree
SUMD Sum of Distances as measure for edge effected incidence of light
n Number of observations
Se Standard error (m)

We can now assess the development of the relationship between the ratio predicted/potential 5-year height increment versus CCF (crown competition). *SUMD* and N_{Taller} are kept constant by inserting the mean values of each tree species. The results in Figure 1 show Douglas fir and the species groupings „Other broadleaves" and „Other conifers" based on data from this study and Douglas fir compared to the results of Common beech and Norway spruce obtaining the parameters from Hasenauer and Kindermann (2006).

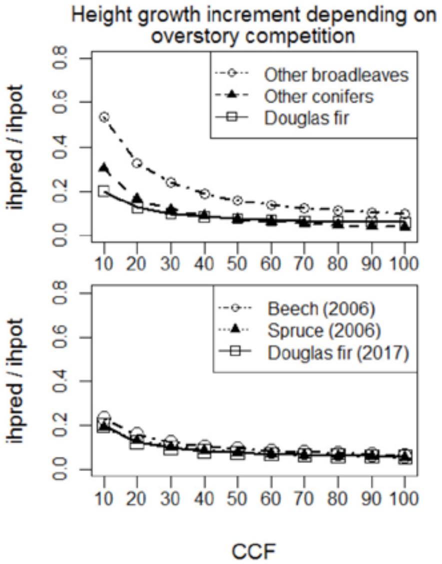

Figure 1: Increase in the relative 5-year height increment of juvenile Douglas fir trees and species groups versus overstory competition expressed by the CCF (Crown Competition Factor). The figure on top depicts Douglas fir and the groups Other Broadleaves and Other Conifers based on coefficients calculated in this study and bottom graph shows Douglas fir with parameters from this study and beech and spruce with parameters from Hasenauer and Kindermann (2006)

Next the influence of edge effected incidence of light on juvenile tree height growth expressed by the factor *SUMD* is shown (see Figure 2) by keeping *CCF* and N_{Taller} at a constant level using the mean values by tree species. As shown in Figure 2 the influence of edge effected incident of light for Douglas fir declines to almost zero within 60 m.

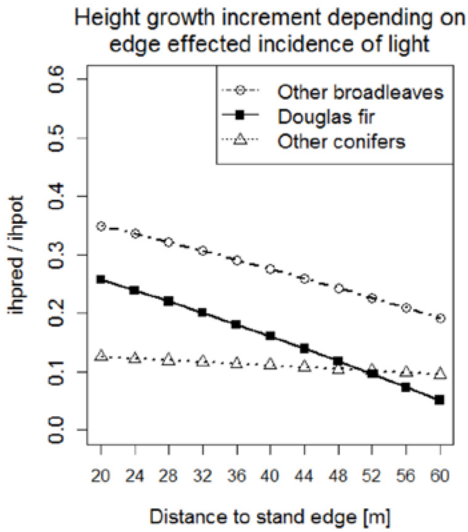

Figure 2: Development of the height-growth rate of juvenile trees versus edge effected incidence of light expressed by the index SUMD. The results show the compensatory effects. Apparently from an additional light supply due to edge effected incidence of light the group „Other broadleaves" benefits most.

4.2 Model evaluation

For assessing the predictive power of our regeneration probability model (see equation 6 and Table 4) we compare the estimated probability of regeneration establishment versus the observed regeneration data from our 28 Douglas fir stands. Since the final decision if regeneration establishment occurs is a combination of a prediction (see equation 6) and a random number, different prediction runs produce slightly different results. Therefore we simulate 20 prediction runs each for all 28 regeneration plots and calculate the ratio of correctly predicted stands. For example, if for a given stand regeneration is predicted and was also evident from the recorded data, the prediction result is classified as correct. The calculated mean percentage of correct predictions was 67.3%. That means 19 of the 28 forest stands were correctly classified.

The evaluation of regeneration density predictions follows a correlation between predicted and recorded densities. After applying equation (7) we perform 20 prediction runs, each comprising all 28 stands. After each prediction run we plot the predicted numbers of regenerated trees versus the recorded numbers to calculate a correlation coefficient. The mean of the 20 correlations coefficients was 0.27.

The juvenile tree height increment model was evaluated by calculating the differences between predicted 5-year height versus recorded 5-year increment so that the confidence (CI), tolerance (TI), and prediction interval (PI) (Reynolds, 1984) can be calculated:

$$CI = \bar{D} \pm \frac{S_D}{\sqrt{n}} \bullet t_{1-\frac{\alpha}{2},n-1} \quad (8)$$

$$PI = \bar{D} \pm S_D \bullet \sqrt{1 + \frac{1}{n}} \bullet t_{1-\frac{\alpha}{2},n-1} \quad (9)$$

$$TI = \bar{D} \pm S_D \bullet g_{1-\gamma,n,1-\alpha} \quad (10)$$

with $\bar{D}$ as mean of differences between predicted and observed values, S_D the standard deviation, *n* the number of observations, *t* the value from t-distribution, 1 – α/2 the quantile of the t-distribution, n – 1 the degrees of freedom and *g* the tolerance factor. Both t-value as well as g-value can be extracted from Kokoska and Nevison (1989). The results are given in Table 6.

Table 6: Mean difference between predicted and observed juvenile height increment by species and height class. The confidence interval (CI, α=0,05) shows the mean of the differences between predicted and observed values, the prediction interval (PI, α=0,05) gives the variation range of the differences between predicted and observed increment, the tolerance interval (TI, γ=0,95 und α=0,05) indicates the error to be expected by applying the model repeatedly (Reynolds, 1984).

Species	Height Class	N	$\overline{ih}_{obs}[cm]$	$\overline{D_i}[cm]$	$S_D[cm]$	*CI [cm]*	*PI [cm]*	*TI [cm]*
Douglas fir	1	24	17.7	3.4	12.0	-1.8 to 8.6	-21.9 to 28.8	-32.2 to 39.1
	2	6	28.0	-1.7	9.4	-12.5 to 9.1	-28.2 to 24.7	-20.0 to 16.5
	3+4	9	45.5	-23.7	11.2	-32.8 to -14.6	-51.0 to 3.5	-44.1 to 3.4
Other	1	19	13.7	7.3	8.2	3.2 to 11.4	-14.4 to 25.1	-16.9 to 31.4
Conifers	2	21	19.7	0.0	6.1	-2.9 to 2.7	-13.1 to 12.9	-16.5 to 16.3
	3	12	32.8	-10.4	11.2	-17.8 to -3.0	-36.2 to 15.4	-39.3 to 18.5
	4	5	36.8	-14.1	23.5	-46.7 to 18.5	-87.1 to 58.8	-53.4 to 25.1
Other	1	12	21.6	5.5	7.1	-0.8 to 10.2	-10.8 to 21.8	-13.3 to 24.2
Broadleaves	2	14	37.6	-12.0	28.9	-29.3 to 5.3	-76.7 to 52.8	-86.4 to 62.6
	3	14	39.5	-10.1	26.0	-25.7 to 5.4	-68.3 to 48.1	-70.6 to 50.4
	4	4	32.4	12.2	34.5	-51.2 to 75.6	-115 to 139	-27.5 to 51.8

N Number of representative trees

$\overline{ih}_{obs}$ Mean observed 5-year height increment

$\overline{D_i}$ Mean difference

S_D Standard deviation

CI Confidence interval (α=0,05)

PI Prediction interval (α=0,05)

TI Tolerance interval (γ=0,95 and α=0,05)

4.3 Model integration in MOSES and analysis of invasiveness

The final step of our work is the integration of the Douglas fir regeneration equations within the tree growth model MOSES to perform simulations according to common forest management scenarios. We did this for several Douglas fir stands and demonstrate here as an example, the Douglas fir stand No 18 of our data (see Table 1). The forest has a stand age 95 years, and the potential natural vegetation is *Asperulo-Fagetum*. The stand covers three tree species, Douglas fir with a relative base are of 67%, Common beech 19%, and Norway spruce with a 14% share of the total base area. The mean diameter of Douglas fir trees is 52 cm, Common beech 7 cm, and Norway spruce 7 cm. Thus the stand comprises an overstory layer dominated by Douglas fir, intermediate and regeneration layer covering all three species. The tree numbers in the understory (see Table 2) shows that Common beech is dominant species followed by Norway spruce and Douglas fir. We simulate the stand for 100 years assuming two management scenarios:

Variant A assumes in the first 5-year period a removal of 50% of the stem volume for Douglas fir, to initiate regeneration, in the second 5-year period 40% of the stem number for Common beech is removed and in the fourth 5-year period the remaining 50% of the volume of Douglas fir is assumed to be harvested.

Variant B assumes the same measures, with the only exception that in second 5-year growth period the stem reduction for Common beech is 80% versus 40% in Variant A.

The results of these simulation runs are depicted in Figure 3.

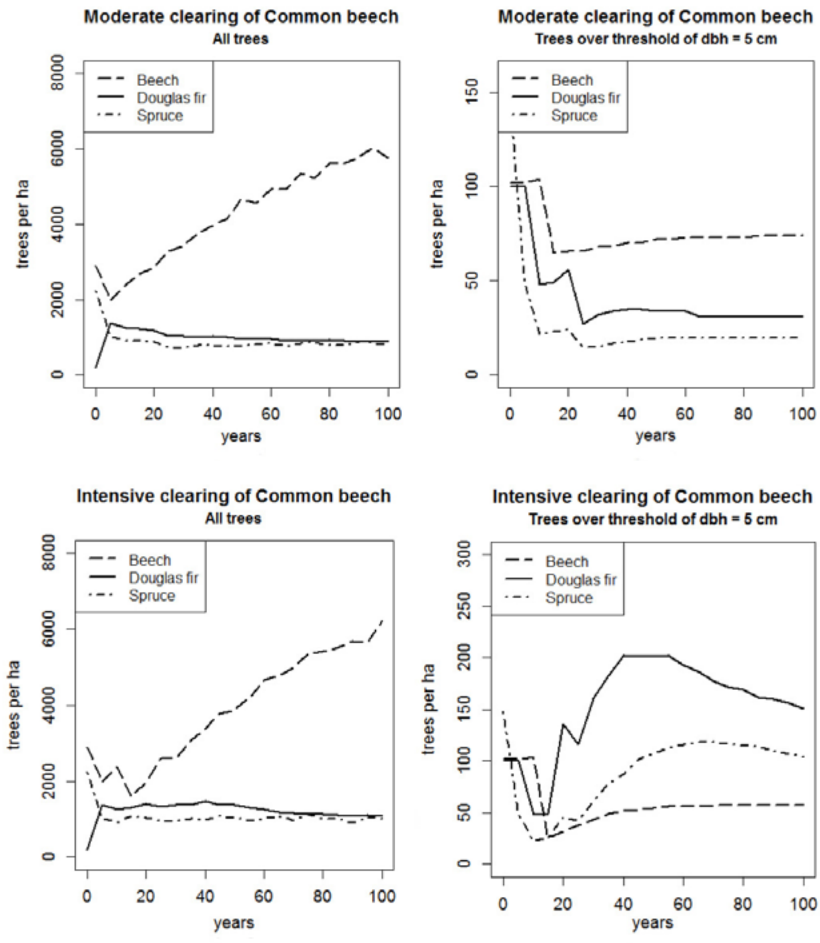

Figure 3: Simulation result with MOSES after implementing the regeneration model for Douglas fir. Stand No 18 is used, the simulation length are 20 5-year growth periods (=100 years). The left plots show the stand development considering all trees. The plots on the right side show the results only for trees with a dbh larger 5 cm. The plots in the top line represent moderate clearing of Common beech in the second growth period (removal of 40% of the stem number) and on the bottom we show results for intensive clearing of Common beech (removal of 80% of the stem number).

5. Discussion

The probability of regeneration within a 5-year growth period (equation 6) depends mainly on the overstory competition and the largest tree by species.

The calibrated model for tree height increment of juvenile Douglas fir (equation 4) strongly depends on overstory competition expressed by the crown competition factor CCF and edge effected incidence of light expressed by *SUMD*. The third parameter, N_{Taller} which addresses the competition within the regeneration exhibited no significant influence (see Table 5).

The residual analysis showed that for 8 of 11 height classes the confidence interval CI is within 5% probability range and shows no bias, PI the prediction interval and TI the tolerance interval exhibited no significant differences for all tested height classes and species groups (see Table 6). The evaluation of the equations (6) and (7) reveals that for the predictions of regeneration establishment and tree density reliable results can be expected.

The consistent model behaviour in future application is also demonstrated by the analyses reflecting from Figures 1 to 3. Figure 1 shows the 5-year height increment of the three species in dependency of *CCF*. Both images of Figure 1 (image above and image below) suggest that even if Douglas fir benefits from an additional availability of light, Common beech apparently profits more and grows faster. The superiority of Other broadleaves is striking in Figure 1, picture above. But it is remarkable also in the Figure 1, picture below, where Douglas fir is compared with Common beech and Norway spruce from the study of Hasenauer and Kindermann (2006). Thus Figure 1 clarifies that on the investigated plots beech is the main competitor to Douglas fir, and it´s growing behavior is remarkably in advantage compared to Douglas fir. This suggests that without supportive interventions Douglas fir will certainly not be able to maintain the position of principal tree species in the long run, as it is the case at present on all the 28 plots.

The same result is shown in Figure 2, where the height growth increment by species depends on *SUMD*, the compensation factor for edge effected incidence of light. At a given light level Douglas fir exhibits lower height growth rates versus Common beech, which indicates that Common beech outcompetes Douglas fir.

Considering the outcome of the performed simulations in MOSES (Figure 3) we can observe that in variant A (Figure 3, above), which assumes a rather moderate reduction of Common beech trees in the juvenile phase (removal of 40% of the stem number), the main competitor of Douglas fir, i.e. Common beech is superior in both, the regeneration layer (Figure 3, above, left hand) as well as the top layer (Figure 3, above, right hand). In variant B (Figure 3, below), which involves a much stronger removal of Common beech at the juvenile stage (removal of 80% of the stem number), Common beech is still superior versus Douglas fir (Figure 3 below, left hand). In the top layer Douglas fir is clearly the main tree species at the end of the rotation period (Figure 3 below, right hand).

6. Conclusion

The calibrated equations for predicting regeneration establishment, tree density and juvenile Douglas fir tree height growth reveals unbiased and consistent results. It can be easily implemented in the tree growth simulator MOSES and in combination with the Douglas fir growth functions of the overstory trees it provides a simple but easy to use tool for forest management scenario analysis. The study also demonstrates that the non-native Douglas fir regenerates well naturally but the juvenile Douglas fir trees experience strong competition by the native tree species, mainly Common beech which gradually displaces Douglas fir. This suggests that Douglas fir does not show any invasive behavior on the investigated stands and, if not promoted by forest management, it will be displaced by natural succession of native tree species such as Common beech.

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Paper 2 Eberhard, B. R., Eckhart, T., & Hasenauer, H. (2021). Evaluating Strategies for the Management of Douglas-Fir in Central Europe. Forests, 12(8), 1040.

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Article

Evaluating Strategies for the Management of Douglas-Fir in Central Europe

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Abstract: In view of the increasing demand for forest resources in Europe, it is an option to foster the use of non-native tree species that can keep pace with the rapidly changing environmental conditions, such as Douglas-fir (*Pseudotsuga menziesii*). Thus, sufficient knowledge of how to manage such introduced species is highly required. In this study, we investigate theoretical silvicultural management options of Douglas-fir for forests in central Europe. We follow a three-step approach: (i) we collect the current central European management practices based on 434 Douglas-fir stands managed by 19 forest companies in Eastern Austria and Southern Germany using a survey. (ii) We calibrate and validate a Douglas-fir parameter set for the tree growth simulator MOSES so that we are able to (iii) simulate the silvicultural management options of Douglas-fir management. Our simulation results suggest: in mixed stands, Douglas-fir should be planted in mono-species patches. This leads to about six times higher productivity compared to a random arrangement. Natural regeneration is possible but requires active management at further development since the productivity might decrease up to 86% when growing in association with the highly competitive native tree species, Common beech (*Fagus sylvatica*). Intensive tending, as well as thinning, yields a surplus stem volume production of more than 30% in comparison with a moderate intervention. Even if our simulation results were not validated in the field, this analysis suggests that modeling as a heuristic tool is a useful instrument for forest managers in the decision-making process.

Keywords: Douglas-fir; silviculture; growth and yield; modeling

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1. Introduction

Current ecological, as well as societal developments, suggest that shortages in the wood supply will soon be present on a European level. Climate change causes an upwards shift of the elevation optimum of tree species, regarding altitudinal as well as latitudinal elevation [1]. Tree species with a principal distribution range at higher latitudes and therefore disposing of little alternative area for colonization are projected as losers. In contrast, species located primarily at lower latitudes at present are predicted to extend their distribution range and therefore are considered winners [2]. This corresponds to findings of [3,4] predicting a decline of needle-leaved tree species in the temperate zones of Europe, including a noticeable reduction of economically highly relevant tree species, such as Norway spruce (*Picea abies*) [5]. Moreover, there is evidence that a percentage of European forests will be put out of commercial management and attributed to non-managed reserve areas with predominantly nature conservation purposes [6,7]. At the same time, the demand for sustainable raw materials such as wood is steadily increasing, especially for pulp and paper production [8,9].

One adaptation option consists of the so-called response strategy [10], suggesting a transformation of current ecosystems by changing the present set of tree species in order to create ecosystems suitable for climate change. In this context, we might practice assisted migration of native tree species that dispose of high genetic diversity and therefore are successful in adapting to environmental changes, such as oak (*Quercus* spp.) [11], or we might think to introduce appropriate non-native tree species. In this study, we look at the promotion of the non-native tree species Douglas-fir (*Pseudotsuga menziesii*) within central European forests. Results from research as well as operation suggest that this species copes well with prolonged drought periods [12–16], whereas most of the native coniferous tree species require regular rainfall [17]. In addition, this tree species provides high productivity rates and thus ensures sustainable income for forest companies [18,19].

The Douglas-fir originates from the Pacific Northwest of America and has two distinct varieties, (i) the coastal or green Douglas-fir and (ii) the interior or blue Douglas-fir [20]. It covers about 830,000 ha of forest land in Europe [21,22]. Promoting Douglas-fir requires forest management tools and silvicultural experiences. Many available European studies on Douglas-fir focus on climate adaptability and provenance recommendations [23–30]. Other studies have targeted the ecological effects of introducing Douglas-fir into native forest communities, including its potential invasiveness [31–36]. A third group explores the qualitative and mechanical wood characteristics [37–42].

In Germany, Kownatzki [43] investigated Douglas-fir field trials with the result that if Douglas-fir is planted in mixtures with common beech (*Fagus sylvatica*), homogeneous patches are beneficial to ensure its survival. Additionally, a low initial stem number improves tree stability and promotes social differentiation. Similar findings have been reported by [44–46]. According to [47,48], the initial stem number is crucial for the tree's stability, stand productivity, and timber quality. For further Douglas-fir studies from Europe, we refer to [49]. In the native range of our tree species, the Pacific Northwest, three principal treatment approaches can be discerned: no management in old-growth stands, intensive management at short rotation, and intensive management at long rotation [50–52]. Within the intensive-management approach, we can observe a tendency to focus on preparative measures such as advanced genetics on the one hand, and early operations such as mechanical site preparation and intensive weed control, on the other hand [53–55]. According to [54], the concept of commercial thinning originates from Europe and was applied there a long time before arriving in the Pacific Northwest. For the native range, guidelines for precommercial as well as commercial tinning were developed, e.g., by [56,57]. Note that Douglas-fir is non-native within European forests and management findings from North America may not be applicable to European forests.

Hence, the aim of this study is to develop guidelines for the management of Douglas-fir in central Europe. We adopt the modeling approach (not being followed by validation in the field) and apply a three-step approach. First, we want to detect the current core issues of managing Douglas-fir in the central European context. Second, we aim at developing an appropriate tool that can reproduce and analyze the growth of Douglas-fir in central Europe, based on simulation; and third, we use this tool in order to assess alternative scenarios for the detected treatment issues. Since this study is part of a large Douglas-fir project (CC Douglas see [58]) supported by 19 forest companies located in Southern Germany and Eastern Austria [59], we performed the first work step by collecting and evaluating the experiences of the involved companies with the management of Douglas-fir, based on a survey. Once the key issues for the management of Douglas-fir stands are available, the core research interest of the study will be accomplished, including two aspects:

(i) The calibration of Douglas-fir for the growth simulator (MOSES) as a diagnostic tool for silvicultural scenario analysis.
(ii) The analysis of the long-term impact of different Douglas-fir management variants by running scenarios with the growth simulator, MOSES.

2. Materials and Methods

2.1. Identification of the Principal Douglas-Fir Management Issues, Based on a Survey

For the collection of Douglas-fir management practices, we carried out a survey. The collected information was only used for modeling but not exemplified in field trials. The stands were located in Austria (Upper Austria, Lower Austria) and Germany (Bavaria, Baden-Wuerttemberg, Hesse, Rhineland-Palatinate), and the following topics were assessed: (i) variety/provenance, (ii) site and stand characteristics, the (iii) established species mixture, (iv) planting methods, as well as experiences with (v) natural regeneration, (vi) tending, (vii) thinning and (viii) debranching (see Table 1). In total, 19 forest companies provided management practice information from 434 different Douglas-fir stands, covering a large variety of site conditions, age classes, and species mixtures.

We grouped the information, and as a result, we defined the following main management scenarios requested by forest companies: (i) planting options, (ii) enhancing the survival of natural regeneration, and (iii) thinning strategies to fully utilize the growth potential of Douglas-fir.

Table 1. Summary of the evaluation of the survey practices of planting Douglas-fir in Central Europe. The information comes from 19 forest companies that provided management information of 434 Douglas-fir stands. These stands were only used for the evaluation of the currently practised Douglas-fir management in Central Europe and differ from the stands listed in Table 2.

Variety/Provenance	The principal variety was coastal Douglas-fir (*Pseudotsuga menziesii var. viridis*), origins are Ashford Elbe, Darrington, Snoqualmie River, Trout Lake (USA), Centre Creek, Heffley Lake (Canada) [25].
Site and stand characteristics	Summer warm and dry climate in the Eastern part of Austria, oceanic climate in the Alpine foreland of Austria, and low mountain range in Germany, astonished climate at the northern edge of the Alps; the majority of stands at altitudes 650 m to 850 m, on silicate bedrock with soil depth 30 cm to 120 cm, 14% on limestone with soil depth <15 cm to 30 cm; water balance on silicate sites was moderately fresh to fresh, on limestone moderately dry; 76% of stands are aged <20 years.
Species mixture	The principal associated species were Norway spruce, common beech, silver fir, larch, Scots pine, sessile oak, maple; with stem number of Douglas-fir smaller 0.3 (44%); greater 0.3 and smaller 0.5 (21%); greater 0.5 (14%).
Planting	Use of bare-rooted plants was most common (73%); planting operations performed by concave spade and whole driller (77%), or by planting ditches (18%); spacing from 1.5 × 2.5 m to 5 × 5 m, most common being 1.8 × 2 m; most common initial stem number 2700/ha; portion of Douglas-fir on average was 30%; mixture form principally was tree by tree with Douglas-fir every 5 to 10 m, planting Douglas-fir in rows or groups was rare; planting largely occurs in spring; frequently reported problem was a fail of Douglas-fir due to insufficient initial stem number.
Natural regeneration	Establishment of Douglas-fir under the shelter of mature trees by opening up or group removal; insufficient opening up causes inadequate rooting and poor crown development; threats come from competitive vegetation, especially native tree species, and game damages.
Tending	Most commonly at top height 2 to 6 m (74%), stem number reduction by 30%; sudden drop-down of young Douglas-fir after release, as result of poorly developed roots and crowns (6%); problem was the spread of blackberry (*Rubus fruticosus*) after release.
Thinning	First thinning at top height 8 to 10m (83%), with removed volume 30–50 m^3/ha; subsequent interventions at intervals 5 to 10 years, with removed volume 50–120 m^3/ha; thinning method was future crop tree selection (68%); mentioned problem was a degradation of the crown after thinning due to insufficient thinning and too late thinning (16%).
Debranching	Debranching at top height 8 to 10 m (37%), at 12 to 15 m (44%); debranched section of tree was between 5 and 10 m (77%); reported problem was the big workload.

Table 2. Stand and site-specific information on the recorded Douglas-fir stands, covering stand age, *N*, the stem number; *DH*, the dominant tree height; *Dq*, the mean breast height diameter; *V*, the stem volume, *Elev*, the elevation above sea level; *Annual Temp.*, the mean annual temperature, and *Annual Precip.*, the annual precipitation. The Stands 1–3, 6–8, 11–20, and 29 were established in 2012 and re-measured in 2017 and provide the calibration data (total 17 stands). The remaining 13 stands were established in 2013/14 and re-measured in 2018/19 and were used for validation. The listed stands below differ from the stands used for the survey (Table 1).

Stand	Age	*N/ha*	*DH* (m)	*Dq* (cm)	*V*/ha (m^3)	*Elev* (m)	*Annual Temp.* (°C)	*Annual Precip.* (mm)	Geology
1	90	136	35	52	324	290	9.9	600	Loess
2	84	164	43	62	720	460	9.6	720	Boulders in a sand-loam matrix
3	82	211	43	57	721	560	9.1	790	Mica schist, quartz phyllonite
4	40	399	23	32	278	520	9.3	770	Muscovite gneiss
5	38	558	24	32	371	360	9.5	650	Sand and argillaceous marl
6	52	188	27	39	223	370	9.1	570	Granulite
7	108	61	32	62	219	400	9.0	580	Granulite
8	58	748	33	39	822	430	9.1	640	Granulite
9	43	306	31	39	474	440	8.9	620	Magmatized granite-gneiss
10	42	285	29	39	386	410	9.0	610	Paragneis
11	70	165	39	64	595	330	9.4	960	Rubble
12	121	247	39	59	863	530	7.9	710	Granite
13	110	160	53	81	1317	820	7.1	2100	Carbonate-free, fine sandstone
14	109	76	50	82	740	640	8.0	900	Granite
15	105	108	53	77	829	660	7.9	910	Granite
16	104	207	50	73	821	590	8.3	890	Granite
17	54	324	33	50	650	660	8.1	1110	Gravel in sand matrix, fluvial
18	95	221	43	67	821	810	7.7	1450	Sandstone calcareous marl
19	100	226	48	67	1199	480	8.8	960	Silt, clayey-sandy, often gravelly
20	72	360	37	53	695	680	7.3	900	Biotite-granite
21	58	221	39	52	627	480	8.6	780	Impact breccia
22	62	350	39	49	749	670	8.2	1120	Glacial till, silt, sand, gravel
23	109	146	50	78	1158	660	7.9	870	Gravel, silt, clay, often stones
24	40	544	22	32	245	700	7.7	900	Limestone, dolomite
25	41	612	23	32	391	700	7.8	890	Corallian limestone
26	60	298	37	51	673	890	7.0	1050	Limestone, dolomite
27	51	366	34	41	453	450	9.1	970	Limestone, dolomite
28	50	279	32	48	579	520	8.8	1010	Dolomite
29	53	594	32	30	465	290	9.9	600	Variegated sandstone
30	37	910	28	31	873	460	9.6	720	Variegated sandstone

2.1.1. Planting Options Considering in the Modeling

A total of 90% of our reported plantations exhibited severe problems immediately after planting, resulting in high mortality rates (up to 50%). Within these stands, Douglas-fir was planted in tree mixtures with Norway spruce and beech. Thus, the simulation exercise will investigate the effect of different species mixtures according to different planting regimes, e.g., tree by tree, smaller homogenous species groups, etc. (Exercise 1). The common silvicultural practice in planting mixed species stands is to create patches of only one species where the minimum size of these patches should be about the crown area of a fully mature tree of this species. This addresses the fact that, according to the tree species, juveniles may need different stand densities to ensure self-pruning or to survive from neighboring species competition. With this concept in mind, we assumed a plantation of 2000 juvenile trees as mixed Douglas-fir—common beech—Norway spruce stands. The plantation arrangements in MOSES cover three scenarios: (i) random, (ii) smaller patches or squares, and (iii) larger patches in the form of strips. The site index of Douglas-fir was assumed to be 45, while the site index for beech and spruce was 38, respectively (applying the site index ratios of stand 18 from Table 2, as described in the following chapter). Since we were only interested in the competitive behavior, we applied no further silvicultural measures. The simulation run is 50 years. The stand layouts are illustrated in Figure 1 (top).

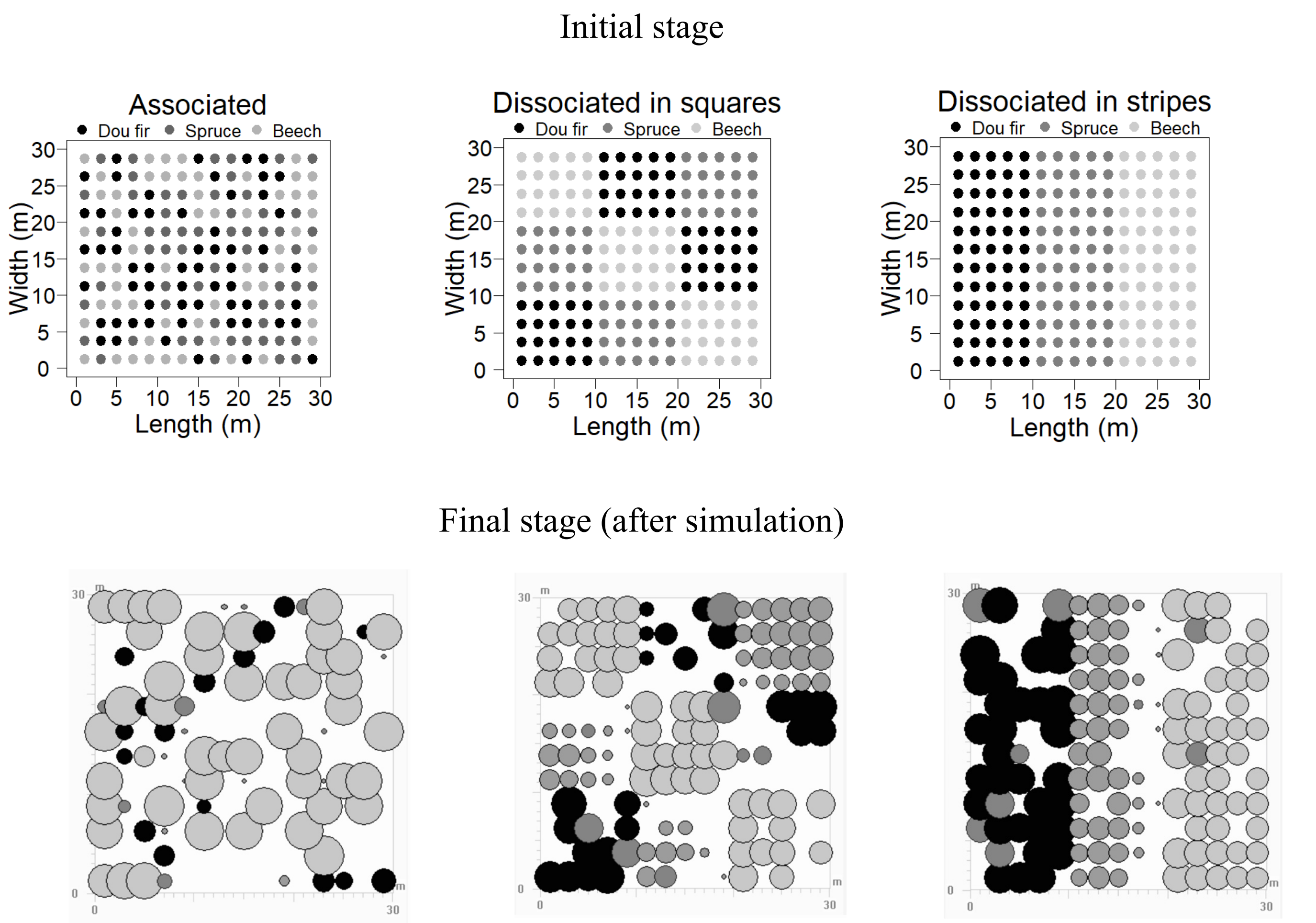

Figure 1. Three different planting variants of Douglas-fir within mixed common beech and Norway spruce stands. The assumed initial stem number in all cases is 2000/ha. The regeneration tool of the MOSES simulator is not active, no tending or thinning is added, simulation period is 50 years. The figures depict the three plantation layouts; (i) random/associated, (ii) square, and (iii) strip. We see the top view on the stand before (top section of the figure) and after (bottom section of the figure) the simulation. The figures on the bottom come directly from the simulator, the dots represent the cross-sectional area of the stems, and for visibility reasons, the diameters are enlarged at 9:1.

2.1.2. Survival of Natural Regeneration

According to the survey, re-establishing Douglas-fir under the shelter of mature trees, mainly in mixtures with Norway spruce and common beech is possible. However, the reported key problems are high mortality rates of naturally regenerated Douglas-fir seedlings and juvenile trees. A simulation exercise will focus on the development of naturally regenerated juvenile Douglas-fir trees in mixtures with spruce and beech (Exercise 2). For our simulations, we selected the Douglas-fir stand number 18 (see Table 2), which represents a mature 100-years old mixed species of Douglas-fir—common beech—Norway spruce forest. The corresponding site indices by species are 45 for Douglas-fir [60], 38 for Common beech as well as Norway spruce [61]. Douglas-fir dominated in the top layer, while beech was the dominant species in the suppressed layer. The basal area by species ranges from 67% for Douglas-fir, to 19% for beech, and 14% for Norway spruce. After initializing MOSES with these data, we activated the regeneration tool for Douglas-fir and the two associated species and ran the model for a simulation period of 100 years to assess the arrival of natural regeneration and the future stand development. Again, we focused on the spontaneous performance of our tree species in competition with the associates, and so we added no silvicultural measures. An illustration of the status of this stand (before the simulation) is given in Figure 2 (top left).

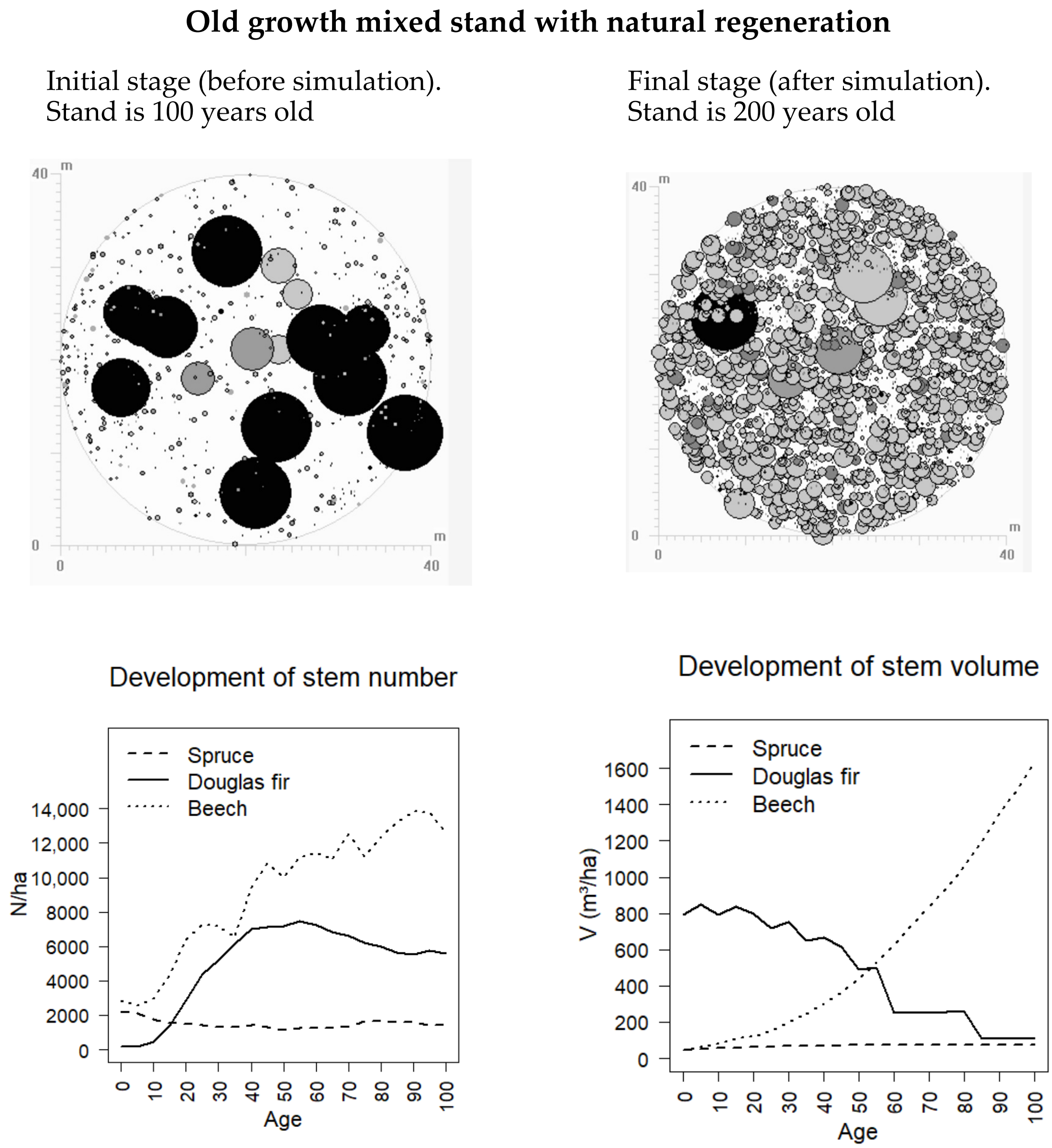

Figure 2. Development of the natural regeneration of Douglas-fir according to simulation with the generated growth model. The demonstrated stand corresponds to a sampled Douglas-fir—beech—spruce stand aged 100 years (stand 18, see Table 2). The simulation period was set as 100 years for the simulation when the regeneration tool was activated. No silvicultural entries were applied. On the top section of the figure, we see the top view on the stand before and after the simulation. The dots represent the cross-sectional area of the stems; for visibility reasons, the diameters are enlarged at 9:1. Black dots stand for Douglas-fir, dark grey dots for spruce, and light grey dots for beech (see also Figure 1).

2.1.3. Tending/Thinning Strategies Considering in the Modeling

From the survey, we learned that tending is done at a dominant tree height between 2 and 6 m, resulting in a stem number reduction of about 30%. Thinning starts at dominant tree heights between 8 and 10 m, harvesting 30 to 50 m^3/ha of the stocking volume if the stand age is less than 30 years, and harvesting 70 m^3/ha and more if the stands are older than 30 years. Since such a thinning procedure may be characterized by several small interventions, the third simulation exercise compares three different thinning strategies (Exercise 3).

Scenario 1—*Questionnaire*: We implemented the above-described baseline strategy taken from the survey as follows: Tending at age 15 with a reduction to 1400 stems/ha, followed by a first thinning at age 25 with a removal of 50 m^3/ha, by a second thinning at age 40 with a removal of about 70 m^3/ha, and by further thinning every 10 to 15 years with removals of about 70 m^3/ha to 100 m^3/ha.

Scenario 2—*Traditional*: Since existing stem number guidelines for Douglas-fir [44] as a general rule suggest very moderate stem number reductions, which is similar to scenario 1, we adopted the common thinning practice of Norway spruce stands [62], resulting in the following assumptions: Tending at age 15 leading to a reduction to 1400 stems/ha, the first thinning at age 25 with a reduction to 700 stems/ha, the second thinning at age 40 with a reduction to 400 stems/ha, and the third thinning at age 55 with a reduction to 300 stems/ha.

Scenario 3—*New*: Tending at age 15 with a reduction to 1400 stems/ha, first thinning at age 25 with a reduction to 600 stems/ha, second thinning at age 35 with a reduction to 275 stems per ha.

In all the scenarios, we assumed Douglas-fir monocultures with an initial stem number of 2000/ha, a site index of 45, and a final stem number of approximately 200 individuals/ha. An important part within the scenario analysis consisted of covering the variability in the thinning effects and the random nature of natural processes. Thus, we executed 10 simulations for each variant and used the mean for comparing the different variants.

2.2. The Tree Growth Model MOSES

As a silvicultural management tool, we use the growth simulator MOSES (MOdeling StandrESponse) [63–65]. It has been used and evaluated for assessing different management scenarios within even and uneven-aged mixed species stands.

MOSES runs on the potential-modifier principle, which implies; (i) the calculation of potential increment rates for both tree height as well as diameter at breast height, and (ii) two modifiers, crown ratio (as the percentage of the crown length in relation to the tree length), and an overstory competition index, as reduction factors addressing the competitive situation of a single tree within the stand. The update of the crown ratio is derived by the change in height to the live crown base. The overstory competition index follows the suggestion by [66]. The model operates stepwise, each growth period comprising five years.

The potential height increment depends on the specific site conditions, expressed by site index functions that describe the development of the dominant height of a stand. For our study, we considered the Douglas-fir site index data published by [67] as well as [60] and re-calibrated the data using a Richard growth function [68]. The potential breast height diameter increment is derived from the potential tree height increment, and the crown width needed for the calculation of the overstory competition index is derived from the tree height at the beginning of a growth period. Both allometric relations (height-diameter and height-crown width) are quantified by using the open-grown tree dimensions published by [69].

In total, the simulator included the following sub tools: the dominant height function, the diameter model for open-grown trees, the crown model for open-grown trees, the taper curve function for the calculation of the volume, the functions for height growth, diameter growth and crown length, the regeneration tool [70], and the mortality tool.

So far, the MOSES model has been calibrated for eight different central European tree species, as well as for Sitka spruce in Scotland. The parameter set for Douglas-fir was accomplished in this study. For this purpose, data from 30 Douglas-fir stands located in Austria and Germany, covering different ecoregions and expressed by a latitude between 47.6° N and 51.7° N, and a longitude between 8.6° E and 16.4° E, were collected. The sampling aimed at capturing Douglas-fir monocultures as defined by a share in the stem number of more than 80%. We established and firstly surveyed the plots between 2012 and 2014, and re-measured all plots between 2017 and 2019, so that, for each tree on a given plot, the five-year growth information for model calibration was available. We recorded the dbh (diameter at breast height), the tree height, the height to life crown, the tree position, and eventual ingrowth or mortality during the five-year period. The threshold for trees to be recorded was 10 cm at breast height diameter. The 17 Douglas-fir stands which were established in 2012 and re-measured in 2017, were used for model calibration, and the remaining 13 stands provided the independent data set for model validation. Summary statistics of the available plot data are given in Table 2; the collected tree characteristics (calibration and validation) by age class are shown in Table 3. Please note that this dataset differs from the 434 above-mentioned Douglas-fir stands of our survey.

Table 3. Characteristics of the trees used for model calibration and validation. The numbers represent the mean as well as the range (minimum and maximum) values by age class. *h* is the tree height, *ih* the five-year height increment, *dbh* the breast height diameter, *id* the five-year diameter increment, *hlc* the height to life crown base, and Δ*hlc* the five-year shift upwards of the height to life crown base.

Age Class	Trees	Characteristics of the Trees (Mean, Min, Max)					
		h **(m)**	***ih*** **(m)**	***dbh*** **(cm)**	***id*** **(cm)**	***hlc*** **(m)**	**Δ*hlc*** **(m)**
Calibration Data							
<30	22	17.7 (10.8–21.1)	1.52 (0.101–2.81)	15.1 (7.12–25.4)	1.61 (0.110–4.32)	8.02 (3.11–10.5)	3.14 (0.122–6.23)
31–50	24	18.23 (11.1–21.6)	1.10 (0.120–2.83)	15.7 (7.91–26.4)	1.31 (0.141–4.22)	8.62 (3.13–11.6)	2.93 (0.101–7.23)
>50	58	24.0 (12.4–47.0)	1.4 (0.143–2.92)	25.3 (9.01–56.5)	1.73 (0.132–3.93)	14.9 (5.54–26.1)	1.74 (0.143–4.92)
Validation Data							
<30	106	22.1 (11.6–29.9)	1.55 (0.102–2.63)	22.4 (8.32–49.5)	1.38 (0.132–5.40)	14.1 (6.62–25.4)	1.10 (0.122–3.81)
31–50	103	22.2 (12.3–33.7)	1.80 (0.112–3.62)	25.2 (7.71–46.2)	1.70 (0.104–4.62)	11.4 (5.73–20.0)	1.70 (0.143–4.11)
>50	124	27.4 (11.5–51.0)	1.70 (0.140–3.52)	33.5 (9.12–97.1)	1.70 (0.144–5.02)	16.3 (5.50–28.1)	1.75 (0.133–4.15)

The open-grown tree dimensions as mentioned above were assumed to be similar to those of silver fir, since test data from 14 open-grown Douglas-fir trees have shown that the relationship between tree height versus crown radius as well as versus *dbh* are similar to silver fir. The predicted values (calculated with the silver fir model) were compared with the observed values, and a Pearson's correlation test yielded R^2 = 0.72 for the crown widths, and R^2 = 0.75 for the diameters.

Since no data for calibrating a mortality function were available, we modified the mortality function for Norway spruce. Based on the stands recorded for the model generation (see Table 2), we evaluated the mean stand, represented by the mean volume and mean stem number. By applying common management guidelines as derived from our survey (Table 1), we adapted the mortality model according to the depicted stem number and volume of the mean stand at age 100.

3. Results

3.1. Calibration of the Tree Growth Model

The general tree growth approach implemented in MOSES has the following form:

$$inc = potinc * CR^a * \left(1 - e^{(b*COMP)}\right) + \varepsilon \quad (1)$$

where *inc* is the actual five-year increment (height or breast height diameter) for each tree, potinc the pre-defined five-year potential increment (height or breast height diameter) according to the site conditions, *CR* is the crown ratio as the percentage of the crown length in relation to the tree length, *COMP* the competition index, *a* and *b* the parameter estimates, and ε the remaining error components. *COMP* consists of the competition at the beginning (ci) and at the end (cicut) of a growth period and is calculated according to $[c_1/(\text{cicut} \times (1 + c_2 \times (\text{ci} - \text{cicut})))]$, c_1 and c_2 representing coefficients. Thus, it explicitly addresses any crown release (e.g., thinning or mortality) within a given five-year growth period. ci and cicut were calculated according to [66].

We next validated the calibrated equations with the available independent data (Table 3) by comparing predicted versus observed tree data. Figure 3 depicts the results for the five-year height and diameter increment functions and the calibrated crown model versus the three key model drivers (i) tree height, (ii) crown ratio, and (iii) competition index.

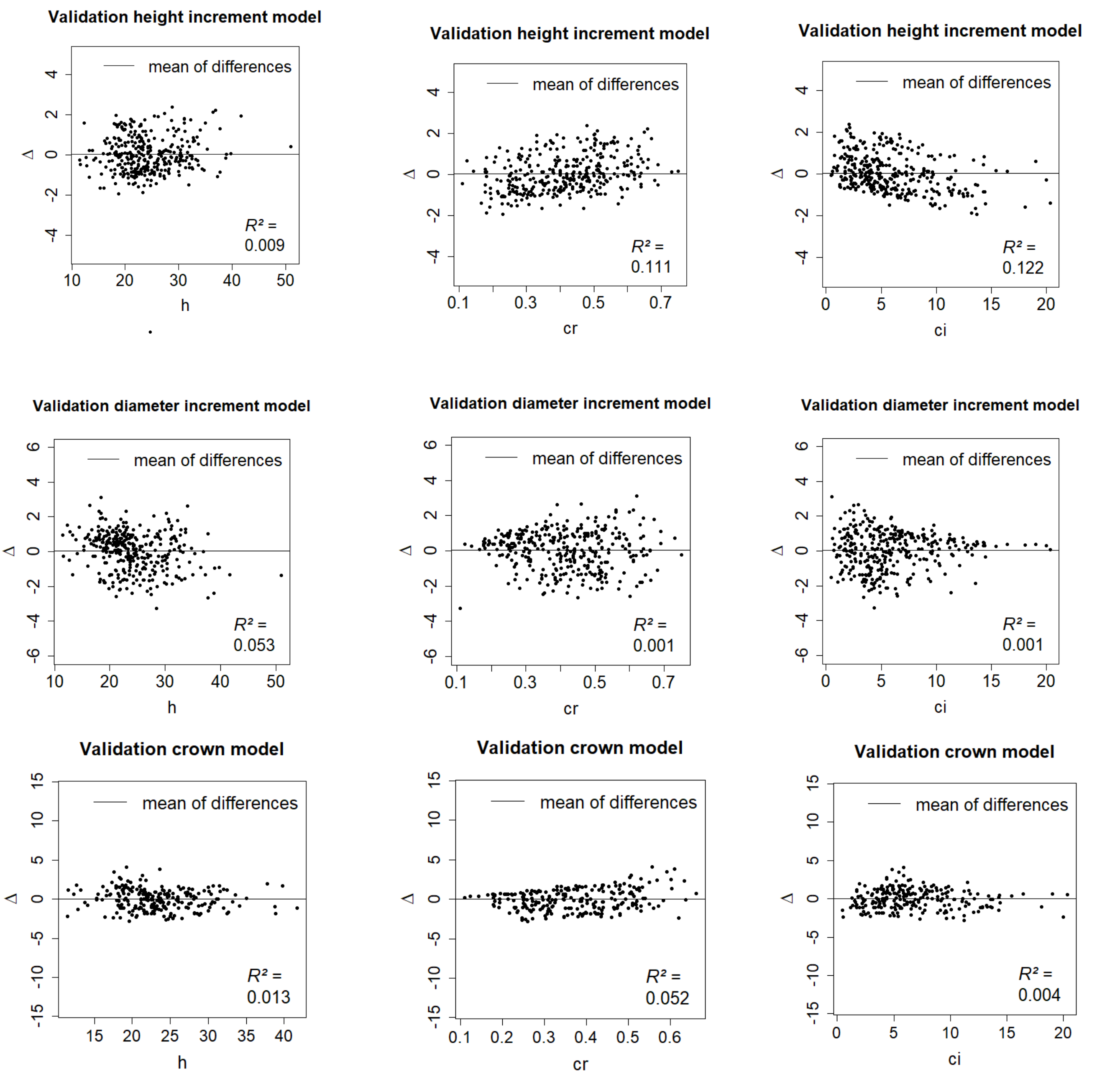

Figure 3. Differences of predicted vs. observed five-year increments using the independent validation data set (Table 3) plotted against tree height (*h*), crown ratio (*cr*), and competition index (*ci*).

Neither regression statistics nor visual analysis of predicted versus observed values provided any information about the consistency of future model predictions. One possibility to determine the limits and range of errors in future predictions is to calculate the confidence, prediction, and tolerance intervals [71]. The confidence interval (*CI*) for the mean of the differences (predicted—observed) can be used to evaluate discrepancies between the expected difference and the estimator:

$$CI = \overline{D} \pm \frac{s_D}{\sqrt{n}} \times t_{1-\frac{\alpha}{2}\ (n-1)} \quad (2)$$

where D is the mean of the differences Di, s_D the standard deviation of the differences, n is the sample size, and t is the $1 - \alpha/2$ quantile of the t-distribution with $n - 1$ degrees of freedom.

The prediction interval *PI* gives the range of the differences among predictions versus observations and is defined as:

$$PI = \overline{D} \pm \sqrt{1 + \frac{1}{n}} \times s_D \times t_{1-\frac{\alpha}{2}\ (n-1)} \quad (3)$$

Finally, the tolerance interval *TI* provides the limit that contains a specified portion (e.g., 95%) of the distribution of the differences when the model is used repeatedly (Reynolds 1984):

$$TI = \overline{D} \pm s_D \times g_{1-\gamma,\ n,\ 1-\alpha} \quad (4)$$

The tolerance factor ($g\ (1 - \gamma, 1 - \alpha)$) for the normal distribution accounting for the probability that $(1 - \gamma)$ 100% of the distribution D is within a probability of $1 - \alpha$ can easily be obtained from statistical tables (e.g., [72]).

The application of Equations (2)–(4) requires that the differences *Di* are distributed normally. A Kolmogorov-Smirnoff test (α = 0.05) found no significant differences from normality. The resulting confidence, prediction, and tolerance interval by site index function [60,67] for deriving the corresponding potentials are listed in Table 4 and can be interpreted as follows: with a probability of 95% we are confident that bias for five-year height increment predictions (ih) using the site index functions of Eckmüllner [60] are between −0.063 m and 0.13 m and thus not significantly different from zero (=unbiased). With a probability of 95%, we can be confident that a single future difference in the five-year height increment predictions will be between−1.69 m and 1.75 m. In repeated model applications, most of the errors (95%) will be between −2.38 m and 2.44 m and suggest that no bias or systematic error is evident and that the calibrated Douglas-fir growth functions will provide consistent and unbiased MOSES simulation runs.

Table 4. Differences between predicted and observed increments within a five-year growth period. The *ih* denotes the height increment, *id* the dbh increment, Δhlc the change to life crown base, x_{obs} the mean of the observed five-year changes in height, diameter and height to crown base, $\overline{D}_i$ the mean difference between predicted and observed values, s_D the standard deviation of the differences. *CI* is the confidence interval, *PI* the prediction interval, and *TI* the tolerance interval at significance level α = 0.05 (see Reynolds 1984). The values between brackets denote the minima and maxima.

	Trees	x_{obs}	**(Min, Max)**	$\overline{D}_i$	s_D	*CI*	*PI*	*TI*
Eckmüllner								
ih (m)	333	1.68	(0.102–3.62)	0.032	0.87	−0.063 to 0.13	−1.69 to 1.75	−2.38 to 2.44
id (cm)	333	1.6	(0.104–5.40)	0.031	1.11	−0.089 to 0.15	−2.15 to 2.21	−3.02 to 3.08
Δ*hlc* (m)	333	1.53	(0.122–4.15)	−0.034	1.31	−0.21 to 0.13	−2.62 to 2.55	−5.32 to 5.26
Bergel								
ih (m)	333	1.68	(0.102–3.62)	0.029	0.9	−0.062 to 0.12	−1.74 to 1.79	−2.43 to 2.49
id (cm)	333	1.6	(0.104–5.40)	−0.245	1.13	−0.36 to −0.13	−2.47 to 1.98	−3.34 to 2.73
Δ*hlc* (m)	333	1.53	(0.122–4.15)	0.133	1.29	−0.02 to 0.286	−2.41 to 2.68	−3.45 to 3.71

3.2. Management Scenarios

After implementing the calibrated growth functions into the tree growth simulator MOSES, it was used as a diagnostic tool to assess the long-term development of different scenarios for our defined exercises.

Exercise 1. *Planting Douglas-fir in mixed species stands.*

By conducting simulations, we investigated if Douglas-fir should be planted in association or in dissociation with Norway spruce and common beech, and if in dissociation, we are interested in what happens in the case of enlargement of the size of the mono-species patches. Figure 1 shows the situation after planting (top) and after the simulated 50-year growth period (bottom). We observed that Douglas-fir disappeared when growing in association, and beech dominated the stand after 50 years (bottom left). When planting Douglas-fir in mono-species groups, a higher survival rate was evident (bottom middle), which lead to even higher Douglas fir tree dimensions after 50 years at an increased size of the patches (bottom right). As shown in Table 5, after 50 years, random Douglas-fir mixtures (association) resulted in stands with 244 Douglas fir stems/ha and 72 m^3/ha stem volume, while dissociated stands grouped in squares exhibit similar Douglas-fir stem numbers (255 stems/ha) but with 258 m^3/ha a much higher stocking Douglas-fir stem volume, which could be even increased to about 355 stems/ha and 483 m^3/ha, if mixtures were planted in long strips.

Table 5. Simulation results of the identified Douglas-fir planting variants according to different mixtures with common beech and Norway spruce: Variant 1: random planting, Variant 2: square or small patches, and Variant 3: strip or larger patches. An illustration of the assumed planting is given in Figure 1. *N/ha* is the stem number per ha, *V/ha* is the stem volume in m^3 per ha, *hL* is the mean height in m, and *Dq* is the mean diameter in cm.

	Random				Square				Strip			
	N/ha	*V/ha* (m^3)	*hL* (m)	*Dq* (cm)	*N/ha*	*V/ha* (m^3)	*hL* (m)	*Dq* (cm)	*N/ha*	*V/ha* (m^3)	*hL* (m)	*Dq* (cm)
Spruce	155	5	11	8	411	140	19	22	422	150	19	22
Dou f	244	72	17	20	255	258	23	33	355	483	25	38
Beech	455	747	25	44	488	487	24	34	444	330	23	30
$\sum$	854	824			1154	885			1222	964		

Exercise 2. *Natural regeneration of Douglas-fir.*

With this exercise, we explored the development of Douglas-fir's natural regeneration within Douglas-fir dominated stands. Since these stands often grow on sites that are potentially beech and/or mixtures of spruce and beech, the competitive situation of naturally regenerated Douglas fir juveniles versus beech and spruce is of interest. Figure 2 shows the situation before (top left) and after (top right) a 100-years simulation run. Evidently, the regeneration tools of the three involved tree species were activated, so that the expected dynamics of the stand development by tree species could be investigated. As shown (Figure 2 top right), after 100 years in the canopy layer the stand was mainly dominated by beech, and Douglas-fir almost disappears. This is evident from the Douglas-fir stem volume development that dropped from 790 m^3/ha to 107 m^3/ha (Figure 2 bottom right), corresponding to a minus of 86%. At the same time, Douglas-fir remained present in the understory, since the stem number increased from 192 to 5570 exemplars/ha.

Exercise 3. *Tending and thinning procedures.*

Next, we are interested in the growth response expressed by the volume and mean breast height diameter development of pure Douglas-fir stands according to different thinning variants. Figure 4 (left hand) displays the run of the stem volume of the three different thinning variants over 100 years. As shown, the variant *New* with the most intensive thinning after two thirds of the observation, exhibited the best results, ending up with 1530 m^3/ha versus the two other tested variants, *Questionnaire* and *Traditional*. Variant *Questionnaire* (1169 m^3/ha) assumed moderate thinning interventions with the result that the growth potential of Douglas-fir was not fully utilized. The variant *Traditional* (1381 m^3/ha) ranged between variants *Questionnaire* and *New*. Figure 4 (right) provides the mean breast height diameter development, and Figure 5 the summed-up values for remaining volume, removed volume, and volume due to mortality by thinning variant.

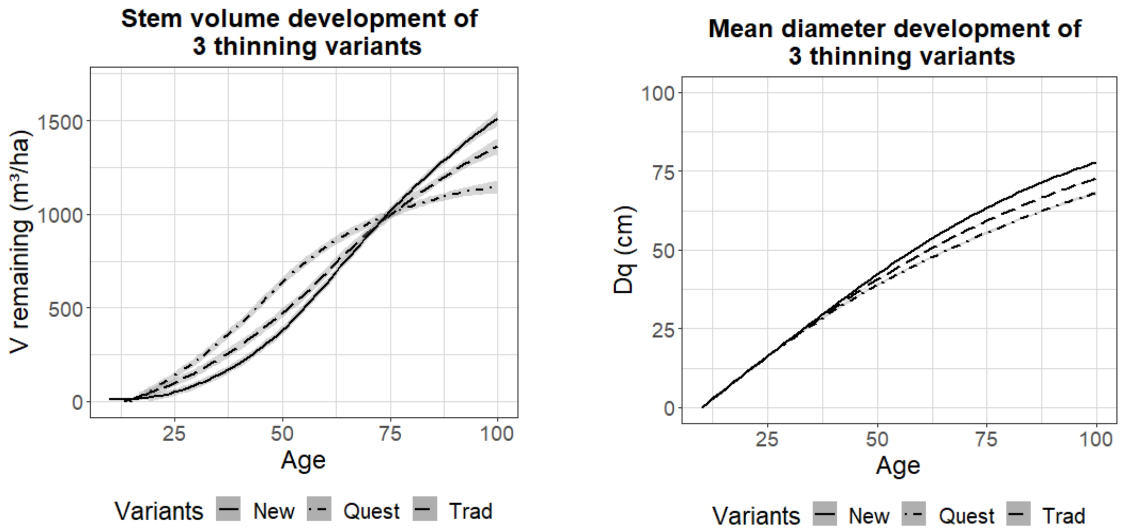

Figure 4. Simulation of three thinning variants of a pure Douglas-fir stand. The variant *Questionnaire* includes many small entries, *Traditional* executes three thinning interventions, and the variant *New* suggests a regime with two early and intensive thinnings. The results show the mean development of 10 simulation-runs, the grey band delineates the confidence interval at $\alpha = 0.05$. The left figure shows the stem volume development, the right figure the mean diameter development vs. age.

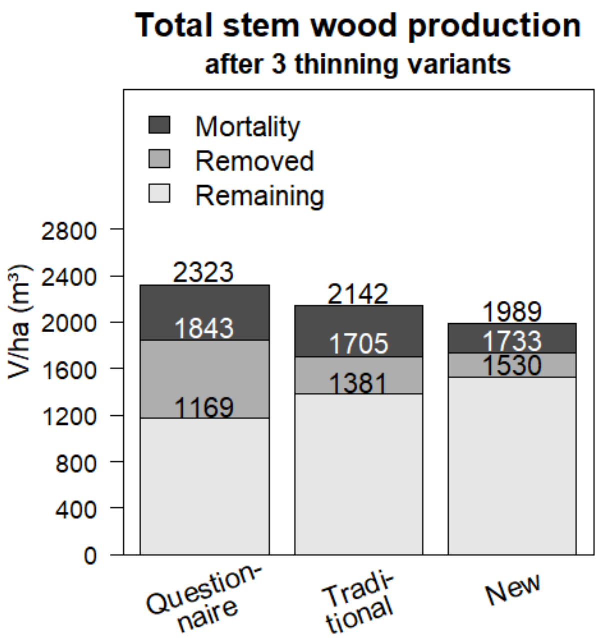

Figure 5. Simulated total stem wood production (remaining volume plus removed volume plus fallen timber/mortality) of the pure Douglas-fir stand after three treatment variants *Traditional*, *Questionnaire*, and *New* (see Figure 4). Variant *New* produces the highest remaining volume, but in terms of total harvested volume (remaining plus thinned), the variant *Questionnaire* is the best.

4. Discussion

Introducing Douglas-fir as an additional tree species to enhance forest management of mixed species forests in central Europe requires management guidelines. Such guidelines may be derived from long-term experimental plots covering different species mixtures, age classes, and treatments, or tree growth models. In this study, we identified current management practices and developed growth parameters for Douglas-fir management in central Europe as required by the tree growth simulator MOSES (MOdelingStandrESponse) for simulating management options. Since the validation results with an independent Douglas-fir growth data set exhibited no bias in the resulting predictions (Figure 3) and the confidence, prediction, as well as the tolerance interval for the height and diameter increment and crown model were unbiased (Table 4), we are confident that MOSES provides unbiased and consistent simulation results.

Since Douglas-fir is often promoted in the lowlands of central Europe where common beech forests are the dominating potential vegetation, it is of high interest to investigate the growth of young Douglas-fir trees in association with beech. The success in planting Douglas-fir in association with beech and spruce (Exercise 1) differs according to the planting regimes. While planting Douglas-fir in random mixtures with common beech and Norway spruce (Figure 1, left) will lead to a dominating common beech stand with only some Douglas-fir trees after 50 years, planting in patches (Figure 1, middle) or larger groups of strips (Figure 1, right) leads to higher survival rates of Douglas-fir juveniles. Increasing the size of a planting gap, e.g., squares of 10 by 10 m in size, results only in intra tree competition and thus ensures a higher survival rate for Douglas-fir after 50 years. As shown in Figure 1, the larger the areas (square to strip) of planting, the higher the chance for Douglas-fir to survive competition from neighboring tree species. This corresponds to findings by [48,73]. The authors conclude that when planting Douglas-fir as an enrichment of naturally regenerated beech, Douglas-fir trees need to be planted in homogeneous patches to avoid competition among species. The different Douglas-fir growth driven by different planting layouts is also evident from the stem volume by scenario. After 50 years, a randomly planted Douglas-fir stand exhibits a stem volume of 72 m^3/ha; if planted in squares, the stem volume production increases up to 258 m^3/ha and reaches even more than 480 m^3/ha if planted in strips (Table 5).

One of the most important silvicultural questions of Douglas-fir management is whether or not natural regeneration occurs and how this regeneration develops in mixtures with native European tree species. Previous studies have shown that Douglas-fir regenerates well [74,75] but may have difficulties surviving due to neighboring competition, mainly from beech [34,43]. This corresponds to reports included in our survey (Table 1), suggesting that natural Douglas-fir regeneration has difficulties surviving in mixtures with native tree species and especially beech, due to sparsely developed roots and crowns as well as a severe competition-induced mortality. This is fully in line with our simulation outputs (Exercise 2), illustrating the development of Douglas-fir natural regeneration in an initially Douglas-fir dominated mixed stand with beech and spruce. As depicted in Figure 2 (bottom left), our tree species has the capacity to arrive, establish and persist on the site over the tested growth period. However, after 100 years most of the dominating Douglas-fir trees disappear due to competition-induced mortality arising, especially from beech, which gradually enters the top layer (Figure 2, top right).

Comparing this situation to naturally regenerated mixed Douglas-fir stands with red alder (Alnus rubra) in the Pacific Northwest, we see a very similar eco-physiological pattern where Douglas-fir was not found beneath red alder, unless management enhanced the competitive situation [76]. Similar findings are reported for planting trials in Germany which show that the survival of Douglas-fir strongly requires planting in homogeneous patches [43]. This is a clear indication that Douglas-fir will require active management to ensure its survival and that no invasive behavior is evident [70].

Our simulations show that the early stage is decisive for Douglas-fir management. This is consistent with findings by [49], who demonstrated that the relief of juvenile mixed

Douglas-fir stands is highly important for future stand development since it has a strong impact on the competition but also the root development. In its natural range, Douglas-fir is a so-called seral species, and as such, it also exhibits the properties of a pioneer [77], with a high demand for light while showing fast growth [13]. Thus, when cultivating the species in mixtures, it is important to take early supportive management actions such as accurate control of the competing vegetation, including the herbaceous stratum and the tree layer, to ensure both survival as well as high growth rates [54].

Finally, we analyzed different tending and thinning options (Exercise 3) as a powerful silvicultural instrument how to control the growth of forest stands. Our simulations showed that the variant *New*, including early and heavy thinning, in terms of stem volume, is superior to the two tested alternatives with moderate thinning (Figures 4 and 5). A thinning regime similar to the here suggested variant *New* is described by [78] for the Massif central/Auvergne in France (with stem reduction to 500 stems/ha in 1st thinning and 300 stems/ha in second thinning, versus the reductions to 400 stems/ha and 275 stems/ha, respectively, suggested here). Apparently, a Douglas-fir stand, being heavily released as in the variant *New*, although including little stem volume initially, after a particular time-period catches up and outperforms (Figure 5, bar plot right hand) a stand that was exposed to light thinning, as effectuated by variant *Questionnaire*. Due to the above-mentioned characteristics of a pioneer species, the remaining young trees react sensitively to the ameliorated conditions and break out in growth. Furthermore, such a stand shows little mortality (Figure 5, bar plot right hand). This might be seen in the context that Douglas-fir reacts sensitively to changes in light availability regarding both growth as well as mortality. On the other hand, when considering the total available stem volume, including the remaining and removed volume, the variant *Questionnaire* with late and moderate thinning likewise represents a reasonable management option (Figure 5, bar plot left hand).

Our simulation results (Figures 4 and 5) are consistent with empirical data from a 134 years-old planted Douglas-fir-forest in Lower Austria. This stand exhibits a mean dbh of 75 cm, a dominant tree height of 56 m, a stem number of 290/ha and a stocking volume of 2400 m^3/ha [79]. This shows that, depending on the site conditions, the potential for Douglas-fir is very high but requires intensive management.

5. Conclusions

With this study, we investigated management measures for Douglas-fir stands in central Europe by exploring the current practices and, based on these management practices, by developing management corridors for key Douglas-fir management questions (Table 1). The three key demanded management options are (i) adequate plantation mixtures, especially in combination with beech, (ii) how to ensure the survival of natural regeneration of Douglas-fir, and (iii) appropriate tending and thinning regimes to optimize and fully utilize the growth potential of Douglas-fir in central Europe. Based on the results of our study, we suggest that Douglas-fir, when mixed with beech, should be planted in homogeneous patches to ensure its survival. Moreover, the study showed that Douglas-fir regenerates well, but the survival is strongly affected by beech, suggesting that Douglas-fir exhibits no invasive behavior. Finally, we can suggest that early and heavy thinning is an appropriate strategy to fully utilize the growth potential of Douglas fir in central Europe.

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Tree marking versus tree selection by harvester operator: are there any differences in the development of thinned Norway spruce forests?

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ABSTRACT

In Europe, Norway spruce forests are facing challenges due to climate change. One possible adaptive option is to enhance the resilience of forests by thinning. Usually, thinning requires two working steps: (i) tree marking by a forest manager and (ii) the harvesting operation. Since the typical tree selection procedure by forest managers is expensive and time consuming, the integration of the tree selection process in the harvesting operation is of high interest. In this paper, we examined four tree selection methods on 21 experimental plots located within eight Norway spruce stands and assessed their impact on the future stand development. The future stand development by tree selection methods was examined by means of a simulation study using the tree growth model MOSES (MOdeling Stand rESponse). The selection methods were (i) tree selection by forest managers, (ii) tree selection by the harvester operator as part of a fully mechanized harvesting system. Since we used the tree growth model MOSES, we additionally employed (iii) a random tree selection process implemented in MOSES, and (iv) a control simulation assuming no thinning. The Norway spruce stands are located in Lower Austria. The results show that 70% of the trees selected by the forest managers were identical to those chosen by the harvester operator and thus no significant differences in the key stand parameters after a 50-year simulation is detectable. Our study suggests that the tree selection for thinning by a trained harvester operator is a cost-efficient and fast method.

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Introduction

Making forests fit for climate change is an important challenge and a key topic for the forest sector. There are two main forest management options in achieving this goal: (i) adaptation and (ii) mitigation (Spittlehouse and Stewart 2003; Millar et al. 2007). Suggested measures may encompass new provenances, resistance breeding, enhancing the genetic diversity, introduction of non-native tree species (Hasenauer 2016), the change in tree species mixtures and stand structure as well as management options to improve the common health and/or resilience of forest stands. In this context, an important management option is thinning, since it reduces the intra stand competition for limited resources. Thus, we can expect that thinned stands may have a higher resilience and are less susceptible to additional future climate change induced stress factors such as drought periods and windthrows.

Thinning reduces intra-stand competition and promotes tree growth of the remaining trees by concentrating the volume increment per unit area following thinning to a lower number of trees (e.g. the remaining "future crop tree"). This reduces susceptibility to stress of the thinned forest stands and enhances the future economic forest value (Dengler 1935; Schädelin 1942; Neumann 2003).

The success of thinning depends on the correct tree selection, commonly done by experienced forest managers. The general rules for tree selection are: (i) identifying a so-called "future crop tree" according to vitality, stability, quality of the trunk and the distribution within the stand, (ii) selecting 1 or 2 main competitors of that "future crop tree" for harvesting, and finally, (3) the non-competitors should remain in the stand because they are important for shading the trunk of the "future crop trees". Consequently, a correct tree marking, i.e. the selection of trees by experienced forest managers prior to the harvesting operation, is one of the most important forest management goals. It affects future stand development, including stand structure, stability as well as the economic value (Havreljuk et al. 2014; Vitková et al. 2016).

In general, a thinning operation (Frank 2008) includes (i) tree marking by a forester as a key pre-requirement, which is followed by (ii) the felling operation according to the selected harvesting system. Tree marking needs experienced forest managers, is time consuming and expensive (Kellogg et al. 1998; Sydor et al. 2004; Cimon-Morin et al. 2010). Thus, large middle-aged forest areas remain un-thinned due to the lack of work force. For example, the Austrian National Forest Inventory suggests an annual thinning harvesting potential of 37% of the total annual cut. In fact, however, the reported harvests from thinning operations are only 13% (FBVA 2009). This leads to large areas of middle-aged forests which may be highly susceptible to snow and/or wind damage. These risks are expected to increase due to climate change.

One option to promote thinning within middle-aged forest stands is to use harvesters and combine the tree selection directly with the harvesting operation. This avoids costs, saves time and is economically efficient. Previous studies have

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shown that the thinning method influences the productivity of the harvester (Cosby et al. 1984; Bergström et al. 2007, 2010), and that no positive effects were evident, if forest managers carried out a tree marking prior to the harvesting operation (Holzleitner et al. 2019). Spinelli et al. (2016) compared the thinning performance of three professional groups, (i) foresters, (ii) loggers/harvesting machine operators and (iii) agronomists by assessing percent removal of the basal area, volume, as well as the mean diameter of the removed trees, with the result that no significant differences were evident. Lexer (1993) compared tree marking by forest managers versus tree selection by harvester operators within broadleaf stands: Again, no significant differences were detectable in the selected trees according to the social class and the selected diameter classes.

The purpose of this study is to compare different tree selection methods when thinning Norway spruce (*Picea abies* (L.) Karst.) stands and assess their impact on the future stand development, including tree growth. We use field data to perform the tree selection exercise and additionally employ the tree growth model MOSES – MOdeling Stand rESponse – (Hasenauer 1994, 2006; Thurnher et al. 2016, 2017), which allows us to simulate the effect of different tree selection results on future stand development and to add two "thinning" variants for comparison. In this study, the following four tree selection methods are applied:

(i) Typical tree marking by professional foresters as a common pre-requirement for the felling operation. Note that any felling operation may be possible (FORESTER).
(ii) Tree selection by the harvester operator as part of a fully mechanized harvesting process (HARVESTER).
(iii) Since we employ the tree growth model MOSES, we use our collected field data and additionally apply a simple random tree selection process as implemented in MOSES (RANDOM).
(iv) Finally, we "apply" a "control" variant assuming no thinning on our field plots for the MOSES simulations (CONTROL).

For assessing the future stand development by tree selection method after thinning, we use volume growth as a measure of stand productivity and height – breast height diameter ratio (H/D-ratio) as a measure of the stand stability.

Materials and methods

Study design and data collection

For our analysis, we selected eight even-aged Norway spruce stands provided by four different forest companies. The stands are located in the northern part of Austria near the Czech border, in the forest growth district area nine – Mühlviertel/Waldviertel (Kilian et al. 1994). All selected Norway spruce stands are located at minimum 850 m a.s.l. ensuring that they are within their natural distribution range and thus less susceptible to bark beetle infestation.

In four of these stands, no thinning had been applied so far (first thinning), while the remaining four stands were thinned before and will experience the second thinning intervention (second thinning). The selected stands cover a minimum size of 0.5 ha. On each of the eight forest stands, three rectangular plots with an average plot size of 175 m^2 were randomly placed to cover the within-stand variation but also any potential variation of the tree marking or the harvesting process. Three plots had to be removed due to wind damage during the study. This resulted in a total of 21 experimental plots located within Norway spruce stands being available for our analysis.

Since the experimental stands provided by the companies were not evenly sized, the number of plots taken in each stand varied. Thus, the sample includes four first thinning stands with 13 plots which exhibit a mean age of 43 years, and four second thinning stands with eight plots covering a similar mean age of 45 years. On each plot, the x and y coordinates, the diameter at breast height (dbh), the social class according to Kraft (1884), and the tree damage were recorded for each tree. Kraft's classification describes the competitive situation of a given tree within a forest stand ranging from: 1 pre-dominant, 2 dominant, 3 co-dominant, 4 suppressed, and 5a suppressed below canopy and still alive or 5b supressed below canopy and dead. The tree damage was split in two categories: (i) stripping damage caused by red deer (Cervus elaphus) and (ii) other damage/defects, which include broken tree–tops, forked trees, red rot damage and harvesting damage. The stripping damage was classified as 0, if the damage was ≤5 cm in width, as 1 for damages ≥ 5 cm in width and <100 cm in length, as 2 if the damage was ≥5 cm in width and ≥100 cm in length, and as 3 for all other damages.

Finally, on each of our 21 plots, six trees were randomly selected to record the tree height (h) and the height to live crown base (hlc), so that with existing dbh – height and dbh – height to the live crown base – relationships available within MOSES, the missing h and hlc for all other trees can be calculated. This information is needed to assess the competitive situation for each tree within a stand, to predict the growth response after thinning, run the model simulations, and to predict volume growth. Summary statistics of the recorded field data are given in Table 1.

Tree selection for our thinning

On each of our 21 field plots, we performed a "blind test" to address potential differences in our four tree selection methods: FORESTER, HARVESTER, RANDOM and CONTROL. Note that for the variant CONTROL, we assumed that no trees would be selected for thinning. This ensures (i) that the stand and/or starting conditions were identical for all selection methods, (ii) the independence of the tree selection by method, and (iii) that any detected variation in the future stand development is an effect of the tree selection method, since the stand conditions prior to the thinning are identical. Next, it was important that the forest managers as well as the harvester operators do not know the exact location of our placed experimental plots. Hidden sticks ensured the correct data recording by selection method as well as the plot locations were unknown.

On average, two professional foresters per stand (16 in total) were active in our tree marking exercise. Since all of the four

Table 1. Summary statistics of the eight selected Norway spruce forests. Thin 1 indicates if the first or 2 the second thinning is planned, Elev is the sea level, SI the Site Index according to (Lembcke et al., 1975; Persson, 1992; Schober, 1995), N/ha is the number of stems per hectare, BA the basal area/ha, D the quadratic mean breast height diameter, DH the dominant height according to Weise (1880), V/ha the volume per hectare, and H/D-ratio is the height – breast height diameter ratio.

Thin	Stand	Elev (m)	Age	SI	N/ha	BA (m^2)	D (cm)	DH (m)	V/ha (m^3)	H/ D-ratio
1	1	850	40	35	2053	47	17	21	409	100
1	2	866	50	32	1422	57	22	23	561	92
1	4	920	27	44	1640	41	18	20	356	96
1	8	890	55	34	1537	74	25	26	802	91
2	3	925	40	45	1164	78	30	28	942	86
2	5	885	55	40	848	62	31	31	768	88
2	6	890	42	38	958	53	26	24	557	84
2	7	900	42	43	836	54	28	28	633	86

participating companies engaged different contractors, four different harvester operators thinned the stands. Table 2 contains a description of the involved harvester operators and the applied harvester machines. In fall 2018, the forest managers marked the trees. In the first months of the following winter 2018/19, the harvesting operations took place.

Working steps by tree selection method

We started our field experiment with the method FORESTER (typical tree marking prior to the harvesting operation). The forest managers performed a thinning from above by selecting the "future crop tree". This tree was marked with a colored ribbon. Next, the one to two main competitors for harvesting were identified, using a ribbon with a different color. The remaining trees were not marked since they should remain in the forest. This method follows the aim that about 400 high quality Norway spruce trees/ha should remain and form the final forest stand at the end of the rotation period (Rössler 2014). Under the assumption of two thinning entries, this implies, as a very general rule applied by all the involved foresters, a reduction to about 800 stems/ha in the first thinning, and to about 500 stems/ha in the second thinning. After the tree marking was finished, the selected trees on our experimental plots were recorded and the colored ribbons were removed. Note, the forest managers did not know the location of our experimental plots.

Next, the method HARVESTER (tree selection by the harvester operator as part of the felling process) was employed.

Table 2. Professional characteristics of the harvester operators engaged in the experimental trials.

Characteristic	Operator 1	Operator 2	Operator 3	Operator 4
Age	53	50	55	32
Formal education	Forestry worker with exam	Forestry worker with exam	Education from different sector	Forestry worker with exam
Years of experience with machine	23	10	20	10
Years of experience with tree marking	37	10	40	10
Type of machine	John Deere 1070	John Deere 1070	Timberjack1270D	Komatsu 911

The harvester operators were instructed by the forest managers in such a way that they should select a future crop tree at every 5-6 m in distance and remove either two competitors (first thinning) or one competitor (second thinning). For the choice of the future crop trees, they should adopt the same criteria as implicitly learned from the forest managers when executing the forest manager-marked thinning operations. Once again, no information was provided concerning the location of our experimental plots. Note that this tree selection is followed by an immediate cutting process. After the harvesting operation was finished, the removed trees on our plots were recorded.

With this harvesting exercise, for each of our 21 experimental plots, we have individual tree data sets with the information of removed trees according to the tree selection method. These tree lists were needed to perform the growth response following thinning, using the tree growth model MOSES. The data sets by plot can be summarized as follows: (i) FORESTER with thinning trees selected by forest managers, (ii) HARVESTER thinning trees are identified and cut by the harvester operator as part of the cutting process. In addition, we have (iii) RANDOM: a random selection process of thinning trees implemented in the MOSES simulator, and (iv) CONTROL, which allows the growth simulation, assuming that no thinning has been applied. Table 3 gives an overview of the identified trees by selection method for harvesting.

The growth simulator MOSES

MOSES (MOdeling Stand rESponse) is a distance dependent single tree growth simulator (Hasenauer 1994; Thurnher et al. 2017). Since the simulator uses the potential modifier approach, the Site Index (dominant tree height at age 100) is needed to derive the top height development by tree species. MOSES has implemented several Site Index curves, we selected the function according to Mitscherlich (1919), which has been re-calibrated for Norway spruce by Kindermann and Hasenauer (2005). After determining the SI for our Norway spruce stands, the potential 5-year height increment, i.e. the simulation steps within MOSES, can be derived for each tree within the stand. Potential breast height diameter (dbh) is calculated from the potential tree height at the beginning and the end of the 5 year growth period using the dimensional relationships of open grown trees, denoting trees grown without competition (Hasenauer 1997).

An important feature of MOSES is that tree growth (periodic height and diameter increment) can be calculated as the relative proportion of the growth potential using two competition measures: (i) past competition expressed by the crown ratio and (ii) current competition expressed by an individual tree competition index according to Ek and Monserud (1974). This also allows the model to address thinning effects (i.e. competition index before and after crown release). The competition index is distance dependent, which ensures that any difference in the pattern of the tree selection by method is explicitly covered within MOSES and will thus directly affect the resulting predictions for tree growth. For example, using a distance independent modeling approach would assume an even distribution of trees on a given plot. This ignores potential patterns in tree marking by method and thus possible effects on

Table 3. Description of the 21 field plots (Plot) located within our eight selected Norway spruce forests (Stand). L_{plot} and W_{plot} are the length and the width for the hidden experimental field plot, $N_{/plot}$ the total stem number on a given plot, F_n the number of selected stems by the forest manager (FORESTER), H_n the trees selected and removed by the harvester operator (HARVESTER), and R_n the randomly selected trees using the selection routine implemented in MOSES (RANDOM).

Stand	*Plot*	L_{plot} (m)	W_{plot} (m)	$N_{/plot}$	F_n	H_n	R_n	*Stand*	*Plot*	L_{plot} (m)	W_{plot} (m)	$N_{/plot}$	F_n	H_n	R_n
1	*1*	15	11	40	10	23	14	*5*	*13*	21	11	16	6	9	9
1	*2*	12	11	25	6	12	12	*5*	*14*	13	13	17	7	10	7
1	*3*	13	14	37	16	21	17	*6*	*15*	15	15	26	16	13	15
1	*4*	15	11	36	12	20	14	*6*	*16*	16	13	15	8	6	6
1	*5*	15	11	35	11	18	11	*7*	*17*	18	13	19	10	8	8
1	*6*	15	13	27	7	10	7	*7*	*18*	13	13	14	7	6	6
2	*7*	11	12	18	7	4	5	*8*	*19*	13	17	31	17	12	15
3	*8*	15	15	25	8	8	8	*8*	*20*	10	14	21	13	12	13
3	*9*	12	13	19	7	9	9	*8*	*21*	13	9	20	13	8	11
4	*10*	14	16	31	13	10	10								
4	*11*	12	12	21	10	11	11								
4	*12*	11	13	28	10	13	10								

volume growth or stand stability. For further details, we refer to Thurnher et al. (2017).

Statistical data analysis

A crucial topic of our statistical analysis was to ensure the proper use of testing methods according to the distribution pattern of the collected information (e.g. normally distributed data or not). We applied the Anderson–Darling test (Anderson and Darling 1952) to ensure the normality of a given data set. If a normal distribution was assumed, we used the analysis of variance (ANOVA) to detect differences among means. If data sets violated the normality assumption, the non-parametric Kruskal–Wallis test (Kruskal and Wallis 1952) was used.

The homogeneity of variance for all our samples was tested by Levene´s test (Brown and Forsythe 1974). We applied the Pearson´s Chi-squared test to discover differences in observed frequencies (e.g. tree selection, etc.) by tree selection method. All tests were based on a significance level of α = 0.05. For data management and analysis the R statistics package (R Core Team 2019) was used.

Results

Trees identified for harvesting

We start our analyses by investigating if any pattern existed in the identified trees (see Table 3) according to the selection method. Note that for the variant CONTROL, no thinning was applied, thus it is excluded from this part of the analysis. We used the stem number, the quadratic mean diameter at breast height grouped by the social class of the removed trees within the stand (see Kraft 1884), and the dbh class to assess if any significant differences by selection methods were evident. Table 4, providing the results of ANOVA (analysis of variance) for the first thinning (normality criterion is fulfilled) and of the Kruskal–Wallis test for the second thinning (normality assumption is not satisfied) by tree selection method, suggests that for the first thinning no difference was evident, while in second thinning the quadratic mean diameter differs significantly. However, a post-hoc analysis (Dunn test) revealed a difference between forester and random (α = 0.020) as well as between harvester operator and random (α = 0.046), but no difference between forester and harvester operator (α = 0.735). Table 5 gives the results of the Chi-square test by selection method versus social class of the selected trees, the dbh class and time of thinning (first and second). With regard to the comparison between foresters versus harvester operators only for the dbh classes of the first thinning a significant difference was detectable, while adding the group RANDOM resulted in significant differences for all groupings.

Next, we were interested if the same trees were selected according to the selection method (FORESTER, HARVESTER, RANDOM). Note that the harvester operators were instructed by the forest managers, as mentioned above. Thus, our specific interest was, if (i) the harvester operators in their attempt to mimic the selection method of the forest managers were able to select the same trees, and (ii) if there is a difference versus a simple random tree selection process. Figure 1 illustrates an example of a typical plot situation (plot 16 of our data). As shown, the variant FORESTER selected eight trees, while HARVESTER and RANDOM will remove only six trees. Of these six trees, the harvest operator (HARVESTER) selected five, while the procedure RANDOM

Table 4. Number (N/ha) and quadratic mean breast height diameter (D) of removed trees as selected by the forest managers, the harvester operators, and random. The numbers indicated are means across all plots in the respective group (1st or 2nd thinning). As the applied statistical analyses demonstrate, only the quadratic mean diameter (D) of the removed trees inthe second thinning differed significantly (α = 0.05).

Treatment	Forester		Harvester		Random		Forester-Harvester–Random			
	N/ha	*D(cm)*	*N/ha*	*D(cm)*	*N/ha*	*D(cm)*	*N/ha*	*D*	*N/ha*	*D*
1st thinning	696	19.1	699	17.8	706	21.1	***ANOVA F***		***ANOVA P***	
							0.94	1.98	0.399	0.15
2nd thinning	430	24.6	437	25.9	411	28.9	***Kruskal*** χ^2		***Kruskal P***	
							0.14	6.34	0.93	0.04*

*Significantly different at α = 0.05

Table 5. Mean total number of trees before thinning (N/ha – see first line) and the number of removed trees per hectare by selection method (FORESTER, HARVESTER, RANDOM). Here, we show the number of trees selected by selection method according to social class (Kraft 1884) and the dbh (diameter at breast height) class. Please note that the statistical evaluation has been realized on the basis of the real removals, while the table shows the values per ha.

Treatment	Method	Social class						dbh class (cm)						
		1	**2**	**3**	**4**	**5**	**Σ**	**1–10**	**11–20**	**21–30**	**31–40**	**41–50**	**51-60**	**Σ**
1st thinning	*N/ha*	216	499	490	247	211	1663	144	912	526	72	9	0	1663
	Forester (F_N/ha)	24	147	272	193	60	696	19	405	253	19	0	0	696
	Harvester (H_N/ha)	27	118	234	202	118	699	81	433	175	11	0	0	699
	Random (R_N/ha)	98	190	201	123	95	706	50	388	206	61	0	0	706
2nd thinning	*N/ha*	189	378	189	132	63	951	6	113	485	309	31	6	951
	Forester (F_N/ha)	19	125	112	112	62	430	6	106	256	62	0	0	430
	Harvester (H_N/ha)	38	133	139	70	57	437	6	114	222	89	6	0	437
	Random (R_N/ha)	74	178	74	67	18	411	0	43	215	129	25	0	411
Pearson´s Chi-squared Test														
		df	*χ^2*		*$\chi^2_{5\%}$*		*P*	*df*	*χ^2*		*$\chi^2_{5\%}$*		*P*	
1st thinning	*F_N/ha – H_N/ha*	4	5.04		9.5		0.28	3	10.7		7.8		0.01*	
	F_N/ha – H_N/ha – R_N/ha	8	27.6 .7		15.5		0.01*	6	20.2		12.6		0.01*	
2nd thinning	*F_N/ha – H_N/ha*	4	3.17		9.5		0.53	4	2.17		9.5		0.70	
	F_N/ha – H_N/ha – R_N/ha	8	17.4		15.5		0.03*	8	16.4		15.5		0.03*	

*Significantly different at α = 0.05

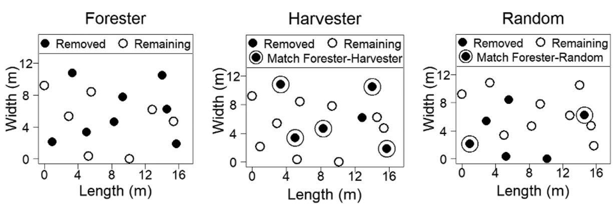

Figure 1. Example for plot 16 of the tree selection by a forest manager (FORESTER), a harvester operator (HARVESTER), and the random procedure implemented in the tree growth model MOSES (RANDOM). The plot demonstrates the initial situation prior to the tree selection and represents the starting situation for the growth simulations.

selected only two of the eight trees proposed by the FORESTER. Consequently, with 62% identical tree selection, the harvester operator mimics the tree selection of the forest managers much better than the random tree selection procedure with only 25% coincidence.

These calculations were done for all our 21 plots. We weighted the results by the total tree number at a given plot to address that plots with more trees may also have more trees selected for thinning. The results show that on average, 67% of the trees selected by the forest managers have been chosen by the harvest operators and only 44% were identical using the procedure RANDOM. In principle, the "correct" selection of trees for harvesting within stands is unknown and there is also a variation among forest managers in selecting trees. However, it is assumed that experienced and well-trained forest managers provide the "best practice" and thus this selection method is often used as a reference.

Tree selection according to tree damage/defect

Thinning promotes individual tree growth and enhances the economic value of the remaining forest stand by specifically selecting damaged trees for harvesting. Prior to the thinning, 37% of our recorded trees exhibited stripping damage, 2% had broken tree tops, 4% of the trees were forked, 3% were affected by a previous harvesting damage and 2% were damaged by red rot.

Regardless of the selection method, the aim of thinning is to reduce the number of damaged/defective trees within a forest stand. Thus, we next analyzed if any difference in identifying damaged trees by selection method was evident. We grouped the number of damaged trees which remained on the site into two groups: (i) stripping as well as (ii) other damages/defects. The stripping damage was recorded in four damage classes ranging from 0 to 3 according to its size (For details see the data section).

After standardizing all numbers to per hectare values (the experimental plots differed in size), we analyzed the number of remaining damaged trees (stripping and other damage/defect) by tree selection method, first and second thinning intervention, and the corresponding median damage class. We were interested in whether the selection method might lead to a bias in the selection process, since an important goal of thinning is to remove damaged trees so that the future economic value of forests can be enhanced. The Kruskal-Wallis test (Kruskal and Wallis 1952) exhibited no significant differences between the tree selection methods. In addition, after analyzing the social class of the removed trees in Table 5, we provide a comparison of the median social status according to Kraft (1884) with classes ranging from 1 to 5, also for the remaining trees. According to the Kruskal–Wallis test, no differences between the categories were evident (α = 0.05) (see Table 6).

Stand development following thinning

Thinning promotes tree growth and enhances the stand value by reducing the number of damaged trees (see previous section). It may also reduce the rotation length due to the fact that the management goals e.g. target diameter, are achieved earlier. Considering our previous results, the next step of our analysis was to assess the impact of thinning on forest growth development according to the tree selection methods applied. For this exercise, we used the distance dependent tree growth model MOSES and simulated the stand development after thinning for ten 5-year growth periods or 50 years. Since the average age of our selected Norway spruce stands was about 50 years (43

Table 6. Comparison of the selection methods FORESTER, HARVESTER, and RANDOM by stripping damage, other damage/defect and social class. The suffix [R] denotes the removed trees, [RM] the remaining trees, [S] stands for stripping damage, and [O] for other damage. N_R/ha is the total mean number of selected and removed trees per ha. N_{RMS}/ha is the mean number of remaining trees per ha with stripping damage, and N_{RMO}/ha the mean number of remaining trees per hectare with other damage/defects. Since all tested data sets violated the assumption of normality, a Kruskal Wallis´ test was applied. In addition, this non nonparametric test takes into account the ordinal character of the damage range (0 to 3) of the trees with stripping damage, as well as of the social class (1 to 5) of the trees.

	Tree selection method	*N_R/ ha*	*Stripping damage*		*Other damage*	*Social class*
Treatment		*Mean*	*Mean N_{RMS}/ ha*	*Median $Range_{RMS}$ (0 to 3)*	*Mean N_{RMO}/ha*	*Median $Status_{RM}$ (1 to 5)*
1st thin	Forester	696	384	1.12	40	2.38
	Harvester	699	433	1.31	38	2.33
	Random	706	412	1.30	43	2.76
	Kruskal-W χ^2		0.32	0.58	0.35	8.64
	Kruskal-W P		0.85	0.75	0.84	0.01*
2nd thin	Forester	430	206	0.25	57	1.75
	Harvester	437	192	0.35	100	1.94
	Random	411	206	0.34	149	2.38
	Kruskal-W χ^2		0.01	0.44	3.97	6.55
	Kruskal-W P		0.99	0.81	0.14	0.05*

*Significantly different at α = 0.05

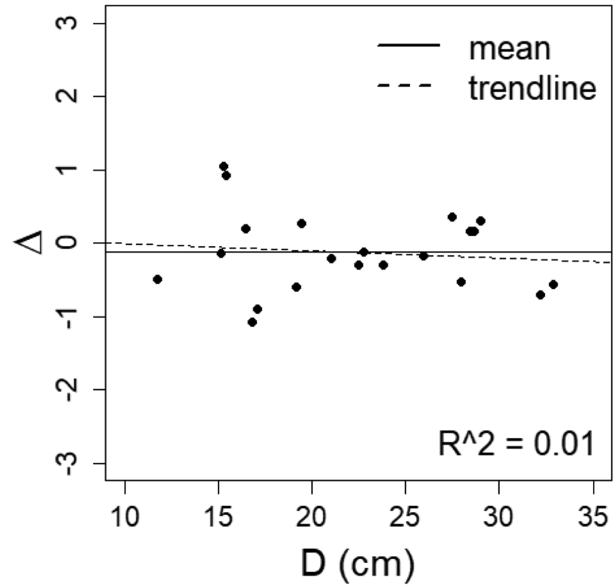

Figure 2. Results of the validation runs by comparing the predicted versus the observed 5-year diameter increment of the central stem (D) on each of the 21 plots, where Δ is the difference between predicted and observed values. Predictions were made by MOSES, observations were taken from increment cores. No significant trend was detectable (R^2 = 0.01), suggesting unbiased and consistent simulation results.

for first and 45 for the second thinned spruce forests – see Table 1), we will get stand predictions for a common rotation period within Norway spruce forests in Austria, which is about 90 to 110 years.

MOSES provides a simple random tree selection procedure to mimic certain stand management options, which we will obtain as variant RANDOM. In this study, RANDOM uses a random number (count) of trees to be removed ranging between the number of selected trees by forest managers and the harvester operators. For each plot, we performed five random tree selection runs, simulated 50 years respectively, and calculated the average values for the resulting target parameters of our simulations, the stem number per ha (N/ha), the quadratic mean diameter (D), the stem volume over bark per ha (V/ha), and the H/D-ratio. We used these average numbers as the thinning results of the variant RANDOM. No distinction was made between the first thinning and second thinning stands.

The fourth variant CONTROL assumed no thinning. The recorded data of our 21 plots were directly transferred to the MOSES model for simulation.

Model validation

An important step in using tree growth models is to ensure that the model reveals unbiased and consistent results. A common procedure for assessing the quality of predictions is to compare them with field data. Since we had one 5-year radial increment core from the "central stem" for each of our 21 sampling plots, we obtained these data for model validation. The term "central stem" refers to the 60th percentile of the dbh distribution and follows a suggestion by Assmann (1970), which showed that the central stem represents the "mean tree" (D = quadratic mean dbh) on a given plot. Figure 2 provides the differences (Δ) between the 5-year increment predictions using MOSES and the corresponding observations. No significant differences (α = 0.05) in the trend line (see Figure 2), as well as the confidence interval (mean –0.11 cm, ranging from – 0.23 cm to + 0.23 cm) were evident. This suggests that MOSES will provide unbiased and consistent simulation results.

MOSES simulations

For each of our 21 plots, four different data sets according to the tree selection method (FORESTER, HARVESTER, RANDOM, CONTROL) were available for the simulations.

Volume development

The growth functions in MOSES explicitly address the thinning effect on forest growth i.e. the effect of crown release expressed by an individual tree competition index. Thus, for each plot, we created four files with identical starting conditions prior to the crown release, but with optional differences in the trees selected for thinning according to the applied tree selection method. The mean corresponding volume removed for the first thinned stands was 192 m^3/ha (FORESTER), 147 m^3/ha (HARVESTER), 244 m^3/ha (RANDOM) and for the second thinned stands 220 m^3/ha, 255 m^3/ha 309 m^3/ha (FORESTER, HARVESTER, RANDOM). The plot-wise analysis of variance (ANOVA) revealed no significant differences (ANOVA F-value 3.41 < F value for α = 0.05) of the volume removed by tree selection method.

After eliminating or better identifying the selected trees in our data sets for each plot, four different stand situations after thinning were available for our MOSES simulations. Since the growth response may differ for the first or second thinning, we split our plots according to this grouping and ran the simulations for each plot, as well as tree selection method to assess the corresponding stand development. Figure 3 provides the results after 50 years by tree selection method as well as for first and second thinned Norway spruce stands. We show the results for the development of the stem number per hectare (N/ha, Figure 3(a,b)), the quadratic mean diameter at breast height (D, Figure 3(c,d)), and the total standing timber volume per hectare (V/ha, Figure 3(e,f)). Figure 4 shows the mean gross stem wood volume production per hectare 50 years after thinning. Again, the results are split by selection method (FORESTER, HARVESTER, RANDOM, CONTROL) as well as first (Figure 4a) and second (Figure 4b) thinned Norway spruce stands.

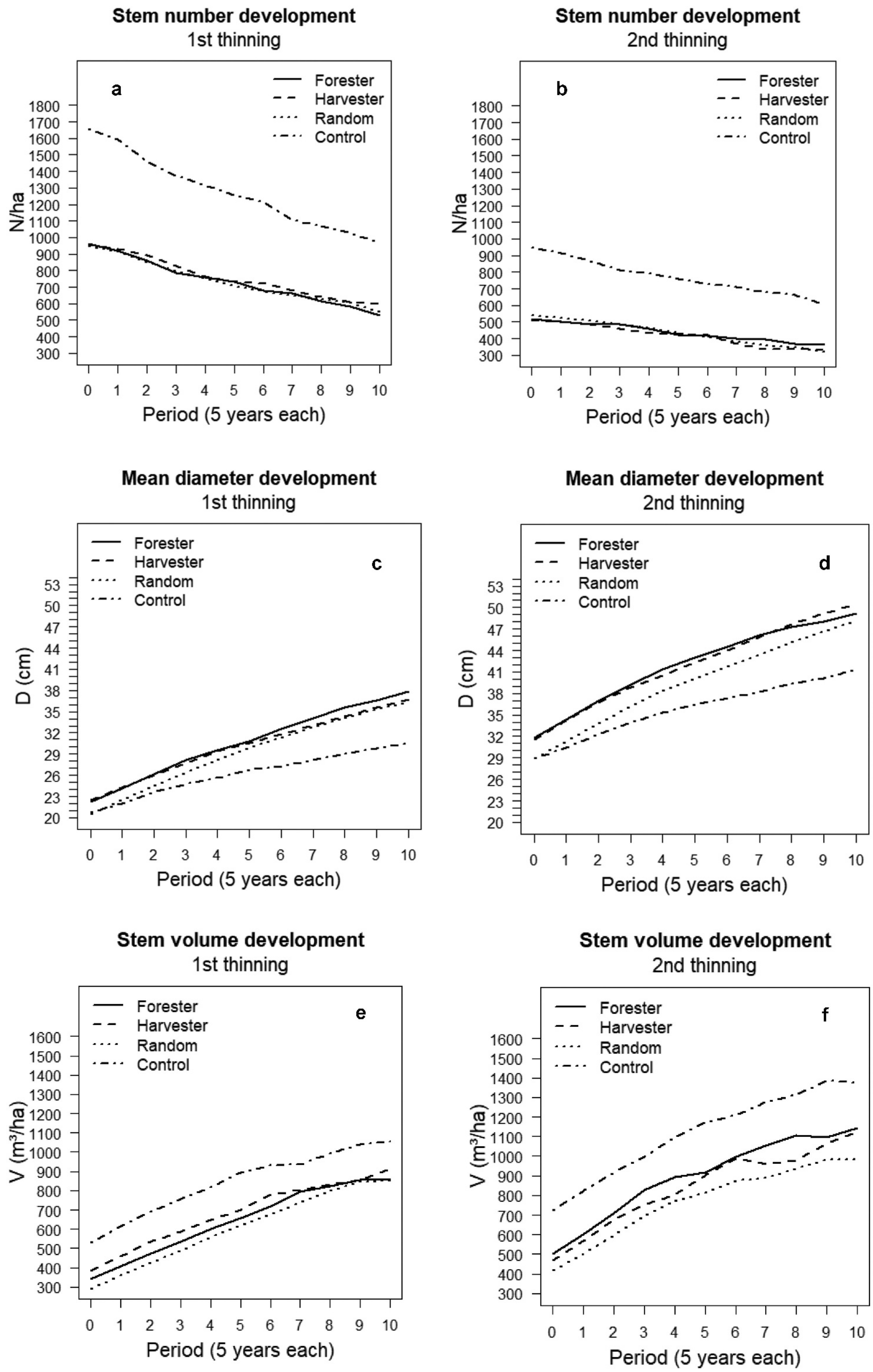

Figure 3. Stem number (N/ha, Figures a, b), quadratic mean diameter at breast height (D, Figures c, d) and standing timber volume development per hectare (V/ha, Figures e, f) for 50 years of growth after treatment according to the tree selection method FORESTER, HARVESTER, RANDOM and no thinning (CONTROL). Note that the average stand age after thinning (Period 0) was 43 years for the first thinning stands, and 45 for second thinning stands.

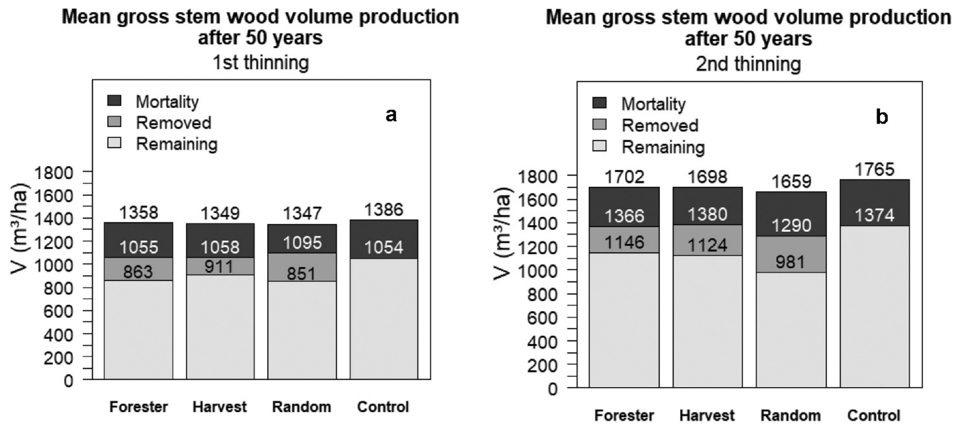

Figure 4. Mean gross stem wood volume production per hectare 50 years after thinning by selection method (FORESTER, HARVESTER, RANDOM, CONTROL) as well as first (Figure a) and second (Figure b) thinned Norway spruce stands. For example, the numbers for FORESTER, first thinning in Figure a can be interpreted as follows: (i) the remaining mean standing timber volume per hectare is 863 m^3/ha, adding the removed volume as a result of the thinning at the beginning of the simulation equals 1055 m^3/ha, adding the simulated mortality during 50 years results in 1358 m^3/ha.

H/D-ratio

An important target of thinning is to improve tree and/or stand stability commonly expressed by the H/D-ratio (tree height (in cm) divided by the diameter at breast height dbh (in cm)). H/D-ratios <80 are considered stable, whereas H/D-values >100 indicate trees or forest stands which are highly unstable (Abetz, 1976; Abetz and Klädtke 2002). Again, for each plot, the mean H/D-ratio was calculated by tree selection method, as well as time of thinning (first and second thinned forests) at the beginning and at the end (after a 50-year simulation run). A plot-wise analysis of variance (ANOVA) and a corresponding Tukey´s honestly significant difference test (Tukey HSD) revealed a highly significant difference (α = 0.01) after 50 years between the un-thinned (CONTROL) simulation results versus the simulations of the thinned variants (ANOVA F-value 6.19 > F value for α = 0.01, first thinned plots, ANOVA F-value 5.41 > F value for α = 0.01, second thinned plots). In Figure 5, the mean H/D-ratio for first (Figure 5a) and second (Figure 5b) thinned Norway spruce at the beginning and after a 50-year simulation are shown.

Discussion

The tree selection by experienced harvester operators as part of the felling process of thinning interventions within Norway spruce forests shows no differences in the future stand development versus the tree selection by forest managers. The number of trees selected as well as the quadratic mean diameter of the trees selected were similar and did not differ significantly (Table 4 with subsequent post-hoc analysis, as described in the text above). The same holds for the tree selection by social class according to Kraft (1884) and dbh class (Table 5). Only the dbh class of first thinning stands differed significantly between forest managers versus harvester operators (Table 5).

Thinning interventions aim for an economic enhancement of the remaining stand by preferring the selection of damaged trees. Thus, we also investigated if any pattern in damaged tree selection between forest managers versus harvester operators was detectable. Once again, no significant differences were evident (Table 6).

An important aspect of thinning is if the damage to the remaining stand due to thinning operations can be reduced by a previous tree marking. In our study such an assessment was

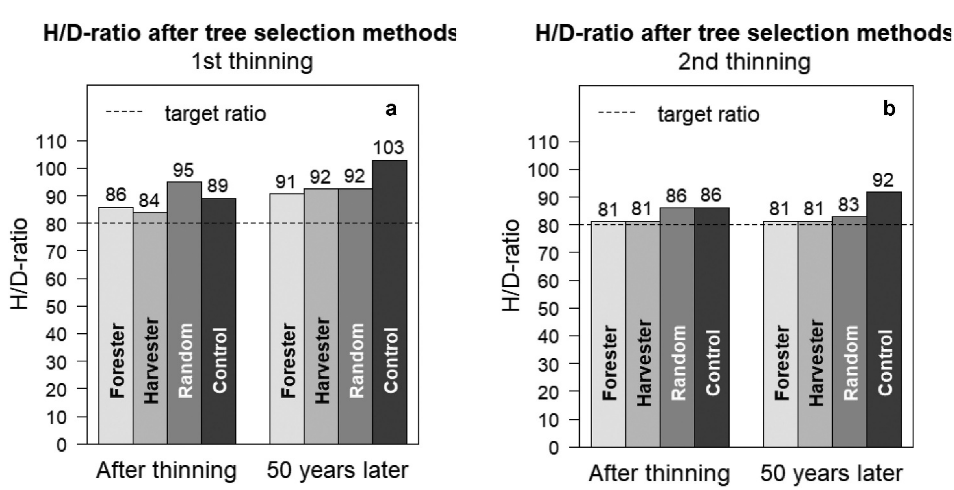

Figure 5. Mean H/D-ratio (height/diameter ratio) for all trees remaining after thinning and at the end of a 50 years simulation period (10 5-year growth periods) using MOSES by tree selection method and first (Figure a) and second (Figure b) thinned Norway spruce stands.

not possible since the tree marking was not followed by a real harvesting operation. A study of Holzleitner et al. (2019), analyzing a first thinning operation, suggestedthat the share of damaged trees after tree marking was lower (3.2% of the remaining trees) as compared to the operator selection (7% of the remaining trees). In contrast, an experiment of (Kuitto and Mäkelä 1988) showed that the number of damaged trees after tree marking increased as compared to the results after operators selection. Moreover, a forest manager who is not familiar with the technical demands of the harvesting machine, could augment the damage. For example, the forester could designate trees for removal that are too far away from the skid road. Indeed, (Lexer 1993) found that at the furthest distance from the machine, the operators remove fewer trees than the foresters.

The results from our study suggest that well trained and experienced harvester operators are able to correctly mimic the common tree selection by forest managers. This is also evident by a high percentage in selecting the same trees (see the example given in Figure 1) for thinning: with about 67% overlap (forest manger versus harvester operator). These results differ from a study reported by Spinelli et al. (2016), in which they showed a poor overlap in the trees selected for thinning according to their background, e.g. forester, logger, or agronomist. Both mentioned studies were realized in conifer forests. In contrast, (Lexer 1993) choose broadleaved stands for the investigation. Although the tree marking under such conditions is even more challenging (Lexer 1993), he found no difference in the performance between forest manager and machine operator, likewise stating that the educational level of the latter is the key aspect. This suggests that a good forest management education and/or well instructed harvester operator are essential for similar thinning results.

At this point it is important to note that, in principle, we do not know the "correct tree selection" (Buongiorno et al. 1995; O'Hara et al. 2012). However, it is commonly assumed that well trained forest managers provide the best silvicultural practice and thus their decision in selecting trees is often used as a reference for other tree selection methods. For our results, it is also important that we obtained data from eight Norway spruce forest stands from four different companies. Each company hired a different harvesting operator and within each of the eight forest stands, two forest managers (in total 16 foresters) did the tree selection for our study. This way, we assume to cover potential variations between different harvesting companies as well as different tree selection approaches among forest managers.

One idea of our study was to add a random tree selection method for thinning as an additional tree selection method in assessing thinned future stand development. The idea was that within forest growth modeling, thinning response and the related stand development is an important part of ensuring sustainable forest management (Hallenbarter and Hasenauer 2003). In our study, we used the distance dependent tree growth model MOSES (Modeling Stand rESponse) to assess thinning effects. Since for larger forest areas, a tree-by-tree selection is not feasible, several growth models such as MOSES often employ a random tree selection procedure to mimic thinning interventions. As shown in Table 4, no difference in the number of randomly selected trees removed (RANDOM) versus the tree selection by forest manager (FORESTER) or the harvester operator (HARVESTER) implemented in MOSES was evident. The same results were evident for the selection of damaged trees (see Table 6). However, the mean dbh of removed trees inthe second thinning (Table 4), the median social class of remaining trees in the first and second thinning (Table 6) showed significant differences between the three groupings. In addition, the tree selection method RANDOM showed significant differences in dbh classes and the social class of the trees selected (Table 5) versus the same grouping of the other two selection methods (FORESTER and HARVESTER). This suggests that any random selection method should be guided by some form of simple stand information to ensure that the random tree selection procedures within growth models mimic the common silvicultural practices as realistically as possible.

A key goal of this study was to analyze whether or not trees selected by method may result in differences in future stand development. For our study, we intentionally selected Norway spruce stands which were thinned for the first time (first thinning) as well as stands which were already thinned once (second thinning). With this approach, we wanted to test if first and second thinned stands may show differences in the future stand development according to the tree selection method. For example, one could expect that a given tree selection method may lead to the same stand parameters at the end of the rotation period versus others, if it is applied to a first thinning intervention, however, it may differ if the same tree selection method is applied to a second thinning intervention.

With the distance dependent tree growth model MOSES, we were able to explicitly assess potential patterns in tree selection and the resulting impacts on tree growth, as well as stand stability. From our validation analysis (Figure 2), we can expect unbiased and consistent simulation results. As shown in Figure 3, the three different tree selection methods (FORESTER, HARVESTER, RANDOM) revealed similar forest stand development parameters for the stem number (N/ha, Figure 3(a,b) the quadratic mean breast height diameter development (D, Figure 3(c,d), as well as the volume development (V/ha, Figure 3(e,f). As expected, the un-thinned variant CONTROL, where no thinning was assumed, exhibited a higher N/ha number, lower D, and higher V/ha development versus the thinned variants. Note that Figure 3 represents the mean development of the plots after the four tree selection methods, for first and second thinning. From Figure 4, which provides the total productivity potential by tree selection method grouped by first and second thinned Norway spruce forests, we learn that there are site quality differences. Since first and second thinning forests are similar in tree age, the latter grow on better sites and thus have a higher productivity potential (Figure 4).

Stand stability expressed by the H/D–ratio (= tree height divided by the diameter at breast height) is a common indicator for tree or stand stability (Abetz, 1976; Klädtke and Kenk 1997; Smith et al. 1997). After thinning, the stand stability expressed by the H/D-ratio was similar for all variants (Figure 5). After 50 years of tree growth, distinct differences between thinned versus un-thinned H/D-ratios were evident.

The H/D-ratio >80 is an indication of instable stand conditions. Fifty years after thinning, the second thinned stands (Figure 5b) exhibited an H/D-ratio of slightly above 80, which may be considered as stable, while the first thinned stands (Figure 5a) may not. The H/D-ratio of these stands is above 90, which suggests that a second thinning would have been needed.

Even though the documentation on costs for tree marking is poor, available reference values suggest 1–3 €/m^3 or 8– 15% of the average harvesting costs (Frank 2008). According to the above-mentioned recommendations by the Austrian National Forest Inventory, the minimum annual cut of regular thinnings should be 7.7 million m^3. Thirty-seven percent of the forest land in Austriahas a slope below 30% and thus is easily assessable by a harvester and forwarder (OpenSlopeMap.org 2021). About 2.5 million m^3 can be thinned by harvester machines. Thus, by assuming an amount of 2 € for tree marking costs, we arrive at an annual saving potential of 5 million € for the Austrian context. Potential cost reductions certainly provide the forest owners with an additional incentive to process the above-mentioned thinning residues, which leads to an increased vitality of the forest stands, and at the same time is beneficial for the satisfaction of the constantly increasing demand of society for raw materials from the forests. When applying the findings of the study, it can be expected that a further investment in the education and the expansion of the silvicultural skills of the harvester operators, will lead to competitive advantages of the respective contractors. As a further effect of this practice, the work variability of a harvester driver is enriched, which entails a boost of engagement and an improvement of the job satisfaction (Lee et al. 2016).

Conclusion

With this study, we can conclude that no differences in the future stand development are evident between tree selection by forest managers versus harvester operators. Experienced harvester operators have very good thinning skills and the immediate cutting following the tree selection may even help to improve the selection process for the next thinning. This may even be an advantage in the tree selection process for the harvester operator (Yeo and Stewart 2001). Finally, it is important to consider adaptation options of random thinning routines, as they are often used as a diagnostic tool to control and/or validate thinning interventions within tree growth models such as MOSES, to ensure unbiased and consistent modeling results.

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